NASA/CR—2001-210767

Ultra-High Power Space Nuclear Power System Design and Development

Rockwell International
Canoga Park, California

March 2001

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Rockwell International
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ULTRA-HIGH POWER SPACE NUCLEAR POWER SYSTEM
DESIGN AND DEVELOPMENT

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INTRODUCTION

This Rocketdyne study of Ultra-High Power Space Nuclear Power System Design and Development (Task 1) is a NASA Lewis Research Center sponsored activity as part of NASA Contract No. NAS3 25808. This task examines the design and identifies technology development requirements for Liquid Metal Cooled Reactor Potassium Rankine Power Systems for Electrical Propulsion at power levels of 10 and 200 MWe, and for power system lifetimes of two and ten years.

Considerable background on liquid metal cooled reactor potassium Rankine power systems has been developed by Rocketdyne over the past several years as one of DOE's Phase I Multimegawatt Space Nuclear Power Supply program contractors. Phase I has just been completed and Rocketdyne as a recent down-select winner, is continuing development of the liquid metal cooled reactor potassium Rankine System in Phase II of DOE's MMW program. Extensive use of system analysis codes and design and development data developed during Phase I of the MMW program has allowed the development of much more extensive and detailed design/development information for the potassium Rankine power systems studied in this Ultra-High Power Space Nuclear Power System Design and Development task than could normally have been generated by the level of effort provided for this task.

The liquid metal cooled UN-W/25Re cermet fueled reactor selected as most appropriate for MMW potassium cycle applications in the DOE MMW program was employed in this study. The metallic matrix provides excellent thermal conductivity and constrains fuel swelling. A peak burnup of 25% should be achievable since the small UN fuel particles are only about 85% dense. The reference 200 MWe reactor with a 10 year lifetime weighs about 59,000 Kg. It has been suggested that an alternate reactor concept[1,2], which uses liquid metal cooled recirculating tungsten or molybdenum clad UC_2 fuel pellets could result in a reactor mass of about 10,000 Kg. However, a definitive conceptual design for such a reactor concept has not been developed and the compatibility and burnup capability of the clad carbide fuel is too uncertain to consider for a reference reactor mass. Although a reactor mass of 10000 Kg appears too optimistic for a 200 MWe 10-year recirculating pellet fueled reactor,perhaps a mass savings of 15000 to 20000 Kg over the reference approach might be possible if such a design ever proved feasible. The potential system mass savings for the 200 MWe two-year or 10 MWe systems would not be near as significant.

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[1] J. Sercel and S. Krauthamer, "Multimegawatt Nuclear Electric Propulsion; First Order System Design and Performance Evaluation" IAA Space Systems Technology Conference, June 9-12, 1986, San Diego, CA

[2] D. Buden and J. Angelo, "Space Reactors - Past, Present, and Future", Proc. 18th IECEC, 1983, Orlando, FL

1.0 SUMMARY

A potassium Rankine cycle Ultra-High Power Space Nuclear Power System was designed for Electrical Propulsion applications of 10 MWe and 200 MWe and for mission lifetimes of two and ten years. A single lithium cooled reactor/primary loop is coupled to three active power conversion systems to develop the power. For two year missions a single redundant backup Power Conversion System (PCS) is provided and for ten year missions, two backup PCSs are provided to achieve the desired mission reliability. Only rectification is employed for power conditioning to produce the 10,000 vdc power required.

Table 1.0-1 summarizes the overall characteristics of the potassium Rankine system. Figure 3.1-1 shows the system schematic and Figures 3.2-1 and 3.2-2 show the overall system configurations.

The potassium Rankine cycle exhibits high efficiency at high radiator temperatures resulting in lightweight, low area systems. Table 1.0-2 summarizes the system performance characteristics. The ten-year mission masses are seen to be significantly heavier than the two-year missions because of the increased reactor mass (more fuel), and because an extra PCS is required to achieve the same reliability for the longer mission.

Table 1.0-3 shows potential weight savings that could reduce the overall system mass. A slightly off-optimum mass design point was selected for the 200 MWe systems to reduce radiator area/system length. A 6000 Kg mass savings could be achieved by selecting the minimum weight point at an increased area/length penalty of about 4%. A man-rated radiation dose limit of 5 R/yr was employed in this study. A 900-1500 Kg shield weight savings for the 10 MWe systems and a 5600-7500 Kg savings for the 200 MWe systems could be achieved if a dose limit of 30 R/yr (50% of the total allowed to astronauts) were employed. A further weight savings of up to 6500 to 80,000 Kg for 10 MWe and 200 MWe systems could be achieved through additional advanced technology development in the areas of advanced radiators, carbon-carbon components and ceramic turbine materials.

Assessment of the technical risks was performed at the individual component level. The conclusion of the assessment was that research was needed in three areas prior to the start of full-scale development. The areas were: Cermet fuel performance, carbon-carbon composite coating, manufacturing and joining, and long-term reliability of high temperature electromagnetic pump materials.

On a "crash" program basis, the major technical feasibility issues can be resolved and the system developed, qualified, and be ready for launch in 9 to 11 years for a 10 MWe system and 11 to 13 years for a 200 MWe system. For a more normally paced program, the corresponding times are 12 to 14 years and 15 to 17 years, respectively.

The total costs from inception to launch (including the first-flight system) are estimated at $2.3 billion for the 10 MWe system and $5.8 billion for the 200 MWe system.

Realization of the weight savings attributed to the advanced technology areas mentioned above would require additional development time ranging from 3-5 years for the carbon-carbon components and ceramic turbine materials to 5-7 years for the advanced radiators.

TABLE 1.0-1
NUCLEAR POWER SYSTEM OVERALL CHARACTERISTICS

<table>
<tr><td>ELECTRICAL POWER</td><td>10 MWE</td><td>200 MWE</td></tr>
<tr><td>REACTOR POWER</td><td>52 MWT</td><td>989 MWT</td></tr>
<tr><td>TYPE OF REACTOR FUEL</td><td colspan="2">UN-W/25RE CERMET</td></tr>
<tr><td>PEAK FUEL BURNUP</td><td colspan="2">25%</td></tr>
<tr><td>REACTOR COOLANT</td><td colspan="2">LITHIUM</td></tr>
<tr><td>REACTOR OUTLET TEMPERATURE</td><td colspan="2">1550K</td></tr>
<tr><td>TURBINE INLET TEMPERATURE</td><td colspan="2">1450K</td></tr>
<tr><td>MAIN CYCLE HEAT REJECTION TEMPERATURE</td><td colspan="2">1000-1025K</td></tr>
<tr><td>AUXILIARY COOLING LOOP HEAT REJECTION TEMPERATURE</td><td colspan="2">650K</td></tr>
<tr><td>POWER CONDITIONING HEAT REJECTION TEMPERATURE</td><td colspan="2">400K</td></tr>
<tr><td>ALTERNATOR COOLING HEAT REJECTION TEMPERATURE</td><td colspan="2">440K</td></tr>
<tr><td>TYPE OF RADIATORS</td><td colspan="2">HEAT PIPE</td></tr>
<tr><td>MAXIMUM HEAT PIPE LENGTH</td><td colspan="2">15M</td></tr>
<tr><td>POWER CONVERSION SYSTEMS - 2 YR MISSION</td><td colspan="2">3 ACTIVE/1 BACKUP</td></tr>
<tr><td>- 10 YR MISSION</td><td colspan="2">3 ACTIVE/2 BACKUP</td></tr>
</table>

TABLE 1.0-2

POTASSIUM RANKINE NUCLEAR POWER SYSTEM PERFORMANCE, CHARACTERISTICS

ELECTRICAL POWER	10MWe		200MWe	
MISSION LIFE	2 YR	10 YR	2 YR	10 YR
SYSTEM EFFICIENCY, %				
- POWER GENERATION	19.4	20.5	19.3	20.4
- POWER CONDITIONING	99	99	99	99
- OVERALL	19.2	20.3	19.1	20.2
SYSTEM MASS, KG				
- REACTOR/SHIELD	5833	11430	28377	72133
- PRIMARY, AUXILIARY LOOPS	10578	11702	197000	216235
- POWER CONVERSION SYSTEM	9652	12060	88040	109975
- HEAT REJECTION SYSTEM	3475	4435	62225	77046
- POWER CONDITIONING	468	468	9360	9360
TOTAL	30006	40095	385002	484749
SYSTEM RADIATOR PLANFORM AREA*, M^2				
- MAIN CYCLE	576	596	11595	11998
- AUXILIARIES	245	245	2980	2980
- POWER CONDITIONING	78	78	1590	1590
- TOTAL	899	919	16165	16568
SYSTEM CONFIGURATION, M				
- LENGTH,	67		344	
- WIDTH (MAX)	35		106	

* ONE-HALF THE EFFECTIVE RADIATOR AREA

TABLE 1.0-3
POTENTIAL SYSTEM MASS SAVINGS

	10 MWE		200 MWE	
	2 YR	10 YR	2 YR	10 YR
BASELINE SYSTEM MASS, KG	30,006	40,095	385,002	484,749
POTENTIAL MASS SAVINGS, KG				
- MINIMUM MASS OPTIMUM 4% AREA/LENGTH PENALTY	------	------	6,000	6,000
- INCREASE DOSE LIMIT FROM 5 R/YR TO 30 R/YR	926	1,490	5,600	7,500
- ADVANCED TECHNOLOGY	6,480	6,480	78,800	78,800
TOTAL	7,406	7,970	90,400	92,300
POTENTIAL SYSTEM MASS, KG	22,600	32,125	294,602	392,449

2.0 POWER SYSTEM REQUIREMENTS

The overall requirements for the Ultra-High Power Space Nuclear Power Systems are listed in Table 2.0-1. Only a potassium Rankine power system is considered. Both 10MWe and 200MWe power systems were developed. Mission lifetimes are 2 years and 10 years and the power output is 10,000 Vdc. The system is man-rated and a maximum of 5 rem/yr is allowed at the dose plane. The dose plane is at 100m for the 10MWe system and at 344m for the 200MWe system. The long dose plane separation for the 200MWe system results from the long radiator lengths resulting from a heat pipe length limit of 15m imposed for practical heat pipe designs. A system reliability requirement of 0.95 was employed for the man-rated mission.

TABLE 2.0-1

NUCLEAR POWER SYSTEM REQUIREMENTS

• TYPE OF POWER CYCLE	POTASSIUM RANKINE
• ELECTRICAL POWER OUTLET	10 MWE AND 200 MWE
• OUTPUT VOLTAGE	10,000 VDC
• MISSION LIFETIME	2 YR AND 10 YR
• SHIELDING-MAN RATED	5 REM/YR AT PAYLOAD
• RELIABILITY	95%

3.0 POWER SYSTEM DESIGN AND PERFORMANCE

3.1 Power System Characteristics/Performance

3.1.1 System Characteristics

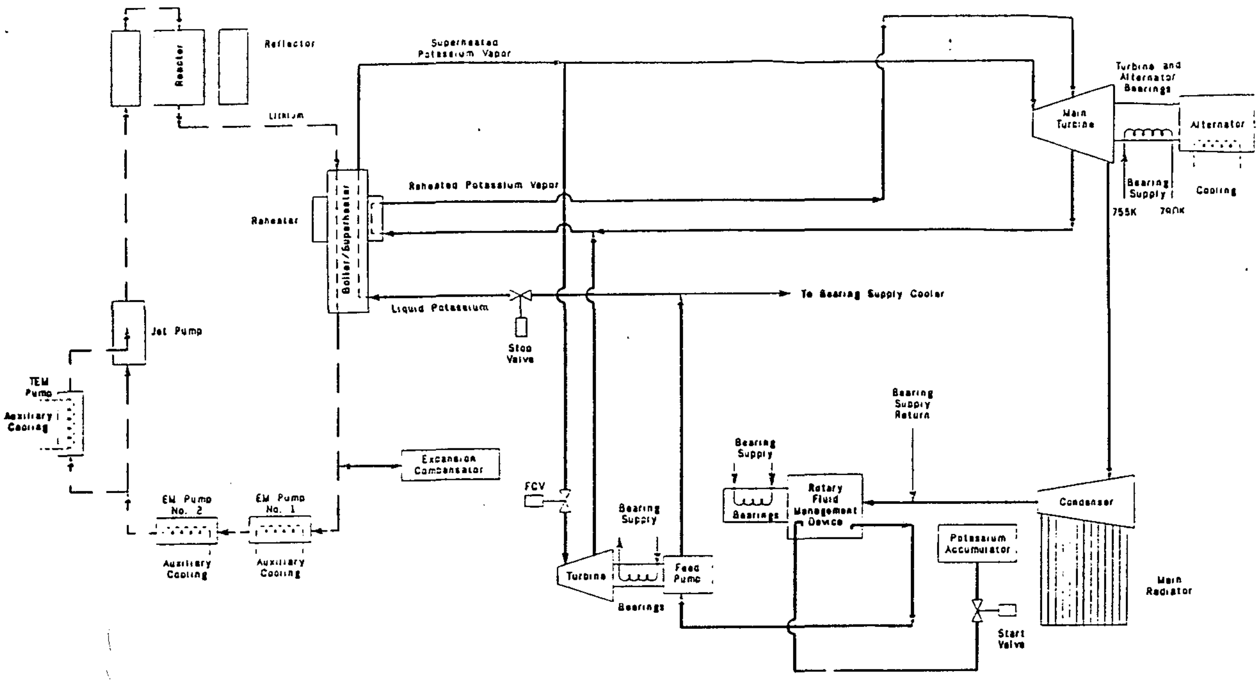
The power system consists of a lithium cooled fast reactor employing UN-W/25Re cermet fuel coupled to the K-Rankine power conversion system. A peak reactor outlet temperature of 1550K and a peak turbine inlet temperature of 1450K were selected based on refractory metal limits.

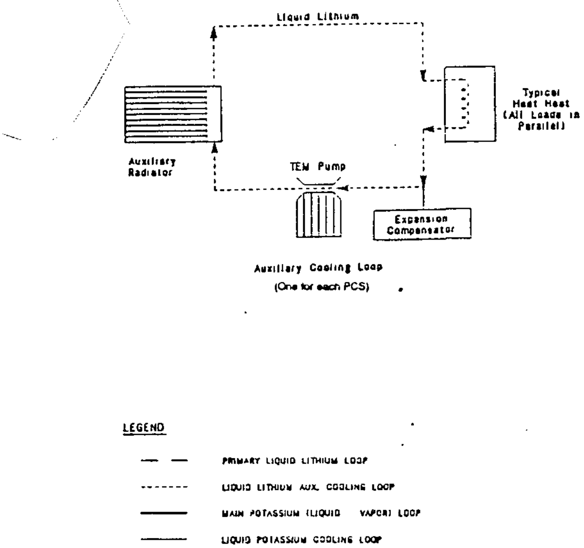
A study was conducted to evaluate the system penalties associated with limiting the reactor outlet temperature to 1350 K (SP-100 technology) rather than 1550 K. In limiting the reactor outlet temperature to 1350 K, the need for heavy tantalum alloys in primary loop, boiler, and in the hot leg piping of the secondary loop is greatly reduced. Lighter weight niobium alloys are sufficient in most instances. Where tantalum alloys are selected, the stress to produce 1% creep is approximately 6 times greater at 1350 K than at 1550 K. This allows for reduced component and piping wall thicknesses resulting in a reduction in mass for the primary loop and for the boiler/reheater. The lower temperature potassium Rankine power conversion system (PCS) requires a reduced heat rejection temperature in order to provide an optimum cycle efficiency. Operating at a lower condenser temperature (925 K vs. 1025 K) results in mass increases to the PCS and the heat rejection system. The low temperature system gives a much higher volumetric flow rate through the reheater, the low pressure stages of the turbine, and through the condenser. This results in larger PCS components. The turbine mass increases primarily due to the size of the low pressure stages of the turbine. The alternator mass increases due to the lower RPM limit of the larger turbine. Decreasing the condenser temperature significantly increases the required heat rejection area. Overall, restricting the reactor outlet temperature to 1350 K results in a 70% increase in required heat rejection area. However, the mass of the system increases less than 10%. The mass increases in the PCS's and heat rejection system are somewhat offset by mass reductions realized in the primary system and boiler.

A study was also conducted to evaluate the benefit of a reactor outlet temperature greater than 1550 K. Increasing the reactor temperature beyond 1550 K results in higher primary system and boiler masses due to the reduced strength of the tantalum alloys. Increasing the wall thicknesses of tantalum components and piping greatly impacts the system mass. The mass benefits realized from improved cycle performance achieved with the higher temperature operation do not offset the mass increases in materials, such as carbon/carbon composites with compatibility coatings will need to be developed to replace the heavy tantalum alloys. Based on these studies, the reactor outlet temperature was limited to 1550 K.

Figure 3.1-1 shows the overall system schematic along with the state points for the four systems. The system consists of three major subsystems; the reactor/primary lithium loop, which extracts heat from the reactor; parallel potassium power conversion loops that pick up heat

Figure 3.1-1 Potassium Rankine Process Flow Diagram





	2 Year Life System			10 Year Life System		
	Temp. K	Pressure KPa	Flow kg/s	Temp. K	Pressure KPa	Flow kg/s
10 MWe System						
Potassium Loops						
H.P. Turbine Inlet	1450	1239	22.9	1450	1239	21.4
Reheater Inlet	1212	425	23.4	1200	392	21.8
Reheater Outlet	1222	425	23.4	1210	392	21.8
L.P. Turbine Inlet	1222	425	23.4	1210	392	21.8
Condenser Inlet	1025	97	23.4	994	76	21.8
Boiler Feed	1024	1314	23.4	999	1314	21.8
Lithium Loop						
Reactor Inlet	1450	227	123.5	1450	227	116.9
Reactor Outlet	1550	181	123.5	1550	181	116.9
Boiler Outlet	1450	124	123.5	1450	124	116.9
200 MWe System						
Potassium Loops						
H.P. Turbine Inlet	1450	1239	461.0	1450	1239	430.0
Reheater Inlet	1212	425	470.7	1200	392	439.2
Reheater Outlet	1222	425	470.7	1210	392	439.2
L.P. Turbine Inlet	1222	425	470.7	1210	392	439.2
Condenser Inlet	1025	97	470.7	1000	76	439.2
Boiler Feed	1024	1384	470.7	999	1384	439.2
Lithium Loop						
Reactor Inlet	1450	395	2486.2	1450	411	2353.0
Reactor Outlet	1550	243	2486.2	1550	250	2353.0
Boiler Outlet	1450	124	2486.2	1450	124	2353.0

from the boiler producing potassium vapor which is converted to electrical energy by a turboalternator; and power conditioning to provide the specified power to the user bus. Auxiliary loops are provided to cool lithium and potassium loop components as well as the alternators.

For the two year mission, the system will consist of one primary loop and 3+1 (3 operating and 1 redundant standby) power conversion loops. From Table 3.1-1 it can be seen that 3+2 power conversion loops are required to achieve similar PCS reliability for the 10-year mission. The use of redundant backup (cool standby) loops was compared to an alternate strategy in which all the loops are operated at partial power until one fails. It was found that the use of standby rather than operating loops produced higher overall system reliability, and reduced the auxiliary heat rejection requirements (bearing cooling, etc.) thus providing a lower mass system.

A reheat cycle is employed to limit moisture content in the turbine. The system design points were optimized for minimum mass for the 10MWe and 200MWe systems employing an optimization code developed by Rockwell on DOE's MMW Space Nuclear Power Supply program. The results of the optimization are shown in Figure 3.1-2. From the graphs, it can be seen that the 2 year mission optimizes at a condenser temperature of 1025K while the 10 year mission condenser temperature optimizes at 1000K. The 1000K condenser temperature provides for a slightly more efficient cycle reducing the reactor fuel mass for the larger reactor (fuel burnup limited) required for long term operation. Because the radiator area for the 200 MWe systems dictate the overall length of the system, a slightly off-optimum design point with a weight penalty of 1-2% was selected which allowed an area (and length) reduction of about 4%. This weight savings could be implemented for a 12m longer configuration if desired.

The reference process flows, temperatures, and pressures for the design points are presented in Table 3.1-2. The reactor power requirements and heat exchanger heat loads are listed in Table 3.1-3. The materials of construction for the system are listed in Table 3.1-4. The major components and piping are ASTAR 811C, T-111 and Nb-1Zr, and the radiators are constructed of carbon-carbon composite to reduce weight.

TABLE 3.1-1

POTASSIUM RANKINE POWER CONVERSION SYSTEM RELIABILITY

MISSION LIFE	2 YR	10 YR
3 ACTIVE AND 1 BACKUP	$\boxed{.9987}$	.972
3 ACTIVE AND 2 BACKUP	.9999	$\boxed{.997}$

☐ SELECTED

BASIS:

	FAILURE RATE, HR^{-1}	PROBABILITY
OPERATION	9.59 E-7	-----
STANDBY	1.69 E-7	-----
STARTUP	--------	.9999

FIGURE 3.1-2
Design Point Optimization

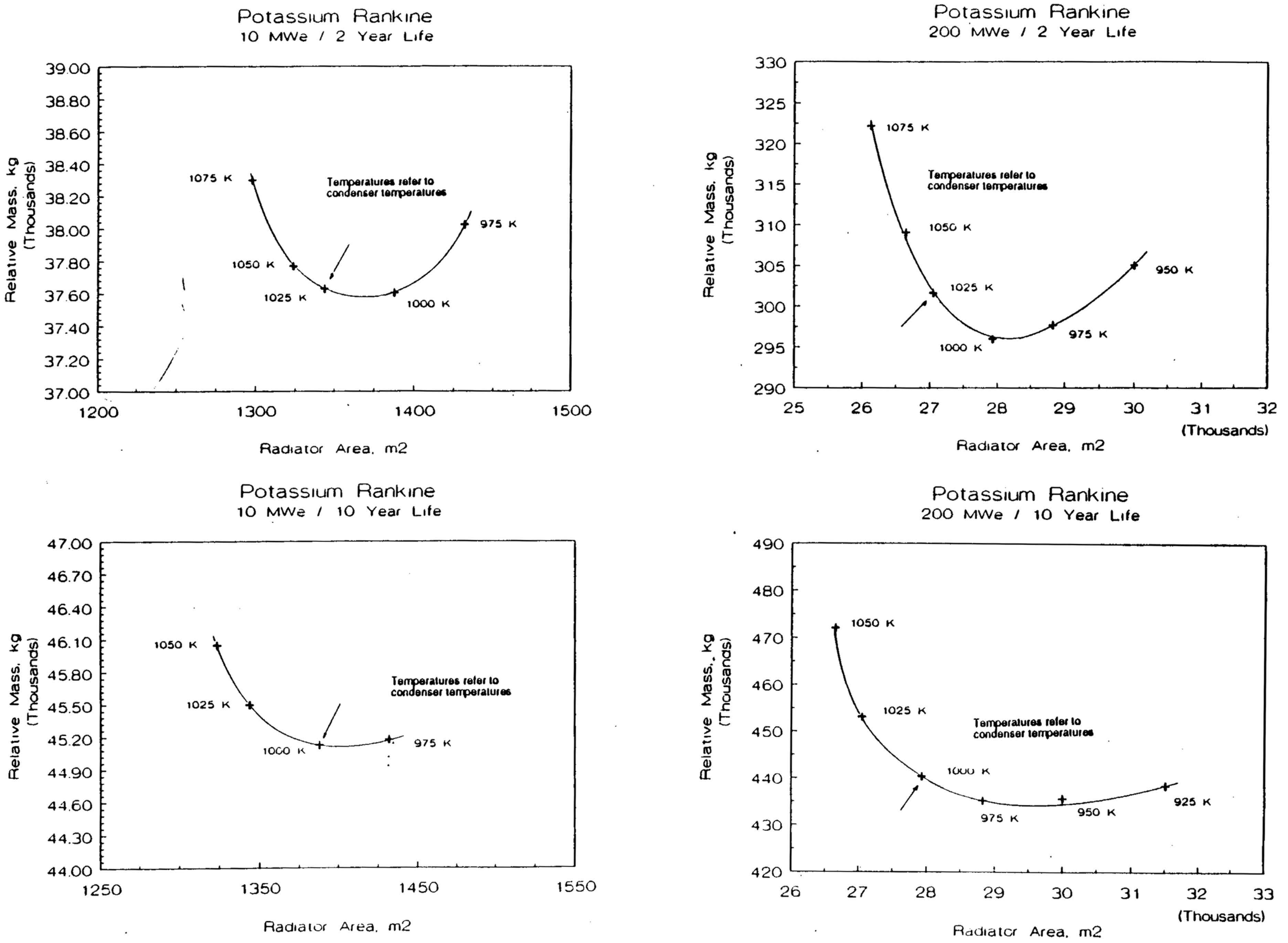


Table 3.1-2 System Design Points

	2 Year Life System			10 Year Life System		
	Temp. K	Pressure KPa	Flow kg/s	Temp. K	Pressure KPa	Flow kg/s
10 MWe System						
Potassium Loops						
H.P. Turbine Inlet	1450	1239	22.9	1450	1239	21.4
Reheater Inlet	1212	425	23.4	1200	392	21.8
Reheater Outlet	1222	425	23.4	1210	392	21.8
L.P. Turbine Inlet	1222	425	23.4	1210	392	21.8
Condenser Inlet	1025	97	23.4	994	76	21.8
Boiler Feed	1024	1314	23.4	999	1314	21.8
Lithium Loop						
Reactor Inlet	1450	227	123.5	1450	227	116.9
Reactor Outlet	1550	181	123.5	1550	181	116.9
Boiler Outlet	1450	124	123.5	1450	124	116.9
200 MWe System						
Potassium Loops						
H.P. Turbine Inlet	1450	1239	461.0	1450	1239	430.0
Reheater Inlet	1212	425	470.7	1200	392	439.2
Reheater Outlet	1222	425	470.7	1210	392	439.2
L.P. Turbine Inlet	1222	425	470.7	1210	392	439.2
Condenser Inlet	1025	97	470.7	1000	76	439.2
Boiler Feed	1024	1384	470.7	999	1384	439.2
Lithium Loop						
Reactor Inlet	1450	395	2486.2	1450	411	2353.0
Reactor Outlet	1550	243	2486.2	1550	250	2353.0
Boiler Outlet	1450	124	2486.2	1450	124	2353.0

TABLE 3.1-3

THERMAL POWER REQUIREMENTS

	10 MW_E		200 MW_E	
	2 YEAR	10 YEAR	2 YEAR	10 YEAR
REACTOR THERMAL POWER, MW_T	51.9	49.2	1045	989
BOILER HEAT DUTY, MW_T	51.0	48.3	1026	972
HEAT REJECTION				
MAIN RADIATOR, MW_T	40.5	37.8	815	760
ALTERNATOR RADIATOR, MW_T	0.43	0.43	5.3	5.3
POWER CONDITIONING RADIATOR, MW_T	0.10	0.10	2.1	2.1
AUXILIARY COOLING RADIATOR, MW_T	0.54	0.54	6.2	6.2

TABLE 3.1-4
POTASSIUM RANKINE NUCLEAR POWER SYSTEM MATERIALS

REACTOR FUEL	UN-W/25 Re
REACTOR REFLECTOR	BeO
REACTOR STRUCTURE	ASTAR 811C
BOILER	ASTAR 811C
PRIMARY LITHIUM LOOP HOT LEG	ASTAR 811C
PRIMARY LITHIUM LOOP COLD LEG	T-111
TURBINE ROTOR, DISCS, BLADES	ASTAR 1511C
POTASSIUM HOT LEG COMPONENTS	T-111
POTASSIUM COLD LEG COMPONENTS	Nb-1Zr

	FINS & HEAT PIPES	HEAT PIPE COATING	HEAT PIPE FLUID
MAIN CYCLE RADIATOR	C-C COMPOSITE	Nb-1Zr	POTASSIUM
AUXILIARY LOOP RADIATOR	C-C COMPOSITE	Nb-1Zr	(MERCURY)*
POWER CONDITIONING/ ALTERNATOR COOLING	C-C COMPOSITE	CARBON	WATER

* OR SUITABLE ORGANIC

3.1.2 System Performance, Mass and Area

Efficiency The system efficiencies obtained from the previous overall system mass optimizations are as follows:

	10 MWe		200 MWe	
System Efficiency, %	2 Yr	10 Yr	2 Yr	10 Yr
Power Generation	19.4	20.5	19.3	20.4
Power Conditioning	99	99	99	99
Overall System	19.2	20.3	19.1	20.2

Area Because of the high heat rejection temperatures, the main cycle waste heat rejection radiator area needed for potassium Rankine cycles is quite small. However, additional area is required for primary and PCS component cooling as well as for power conditioning heat loads.

The overall area requirements for the different power systems are shown in Table 3.1.2-1. The effect of the lower main cycle radiator temperatures for the 10-year missions result in slightly higher areas compared to the 2-year mission areas. The auxiliary radiator area requirements are seen to be from 30 to 35% of the total area requirement.

Mass The mass breakdowns for the four power systems are shown in Table 3.1.2-2. For the 10 MWe systems, the radiation shield required is seen to be heavier than the reactor. However, for the 200 MWe systems the larger boiler provides additional radiation shielding, and the increased dose plane separation set by the increased area required result in thinner radiation shields.

There are significant weight increases required in going from two-year to ten-year system lifetimes. The reactor mass increases almost linearly with lifetime since the fuel is burnup limited (25%). The need for the extra [(3-2) vs (3+1)] PCS for the ten-year mission is reflected in the increased masses for the PCS, boiler and auxiliary systems. The heat rejection weights are seen to increase somewhat as well. This is because of the added radiator manifold required for the extra PCS, and because of the increased meteroid protection armor required for the longer mission.

The primary heat transport system is seen to be quite heavy. This mass is about equally distributed among the EM pumps, piping and boiler. Direct potassium boiling reactor systems, which eliminate the primary loop, have been evaluated in the past. These evaluations have always shown the mass for the direct boiling system, with its larger reactor and shield, to be about the same or slightly heavier than systems employing a primary loop and separate boiler. For the primary loop system, the separate boiler provides much of the radiation shielding required resulting in a much lower shield mass. To meet long term reliability requirements it is necessary to provide redundant PCSs. For the direct boiling reactor system this would require large PCS valves to isolate backup or failed PCS systems and to activate backup systems. For these reasons and to avoid any reactor boiling stability questions, the indirect system was selected for these systems.

TABLE 3.1.2-1

POWER SYSTEM RADIATOR AREAS, M^2

	10 MWE		200 MWE	
	2 YR	10 YR	2 YR	10 YR
MAIN CYCLE RADIATOR	576	596	11595	11998
AUXILIARY RADIATORS				
AUXILIARY COOLING LOOP	53	53	613	613
ALTERNATOR COOLING	192	192	2367	2367
POWER CONDITIONING RADIATOR	78	78	1590	1590
TOTAL RADIATOR AREA*	899	919	16165	16568

* AREAS LISTED ARE PLANFORM AREA. EFFECTIVE RADIATING AREA IS TWICE THESE VALUES

TABLE 3.1.2-2
POWER SYSTEM MASS BREAKDOWN, KG

	10 MWE		200 MWE	
	2 YEAR	10 YEAR	2 YEAR	10 YEAR
REACTOR/PRIMARY LOOP				
REACTOR	1,683	4,500	13,677	59,133
SHIELD	4,150	6,930	14,700	13,000
PRIMARY HEAT TRANSPORT SYSTEM	5,082	5,082	100,500	100,500
AUXILIARY COOLING SUBSYSTEMS	896	1,120	6,500	8,135
BOILER	4,600	5,500	90,000	107,600
SUBTOTAL	16,411	23,132	225,377	288,368
POWER CONVERSION SYSTEM				
TURBOALTERNATOR	4,828	6,035	56,660	70,825
TURBOPUMP	92	110	1,380	1,650
RFMD	972	1,215	10,440	13,050
PIPING AND AUXILIARIES	3,760	4,700	19,560	24,450
SUBTOTAL	9,652	12,060	88,040	109,975
HEAT REJECTION SYSTEM				
MAIN CYCLE RADIATORS	2,198	2,831	43,058	53,003
AUXILIARY RADIATORS	1,277	1,604	19,167	24,043
SUBTOTAL	3,475	4,435	62,225	77,046
POWER CONDITIONING	468	468	9,360	9,360
TOTAL SYSTEM MASS	30,006	40,095	385,002	484,749

The turboalternator is also quite heavy. The current allowable peak turbine blade tip speed limits the rotational speed of the 200 MWe machine well below that desired for a reasonable alternator mass. This results in a much heavier alternator than would result at higher speed. It may be better to decrease the size of the turboalternators by going from three to four active units to allow a higher rotational speed. This trade study has not been made at these power levels.

As discussed in the next paragraph, development of several advanced technologies could reduce the system masses presented by 6,500 to 80,000 Kg for the two power levels. Additional savings are possible by increasing the allowable radiation dose for the 10 MWe system and by increasing the length of the 200 MWe system as was shown in Table 1.0-3 of the Summary.

3.1.3 Advanced Technology Benefits Assessment

Advancements in a number of technology areas could benefit the nuclear potassium Rankine power system. Those that could provide significant mass savings to the reference design summarized in Table 3.1.3-1 and discussed in the following paragraphs.

3.1.3.1 Advanced Radiators

A number of advanced radiator concepts have been proposed for application to the problem of rejecting multi-megawatts of waste heat to space. These concepts are generally characterized as having significant mass advantages over the heat pipe radiator concept. A recent assessment of these concepts have been made by Shih, et.al.[1], of TRW, Reference 1. In that study the heat pipe radiator, the membrane heat pipe radiator, the liquid droplet radiator, the Curie point radiator, the rotating membrane radiator and belt radiators were evaluated.

Results of the evaluation are summarized in Figure 3.1.3.1-1. The figure indicates that the most advanced of the concepts could provide a specific panel mass of 0.02 Kg/KWt. The radiators used in this study result in specific mass values of about 1.40 Kg/KWt of effective radiating surface area. Use of the most advanced concept could, therefore, result in a mass savings on the order of 40,000 Kg for the 200 MWe, 10 year life version. It must be noted, however, that only very preliminary laboratory scale demonstrations of these advanced concepts has been made.

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[1] Shih, C. C., Sollo, C., Boretz, J. E., Lissit, S. A., "Non-Nuclear Multimegawatt Pulsed Power Systems/Lithium-Hydrogen Chemical Reactor Study", AFWAL-TR-88-2066, 30 September 88, AFWAL-WPAFB, Ohio

TABLE 3.1.3-1
POTENTIAL ADVANCED TECHNOLOGY BENEFITS

	10 MWE	200 MWE
ADVANCED RADIATORS	2000 KG	40000 KG
CARBON-CARBON COMPOSITE MATERIALS APPLICATIONS	3000 KG	20000 KG
CERAMIC TURBINE MATERIALS	1480 KG	18800 KG
TOTAL SAVINGS	6480 KG	78800 KG

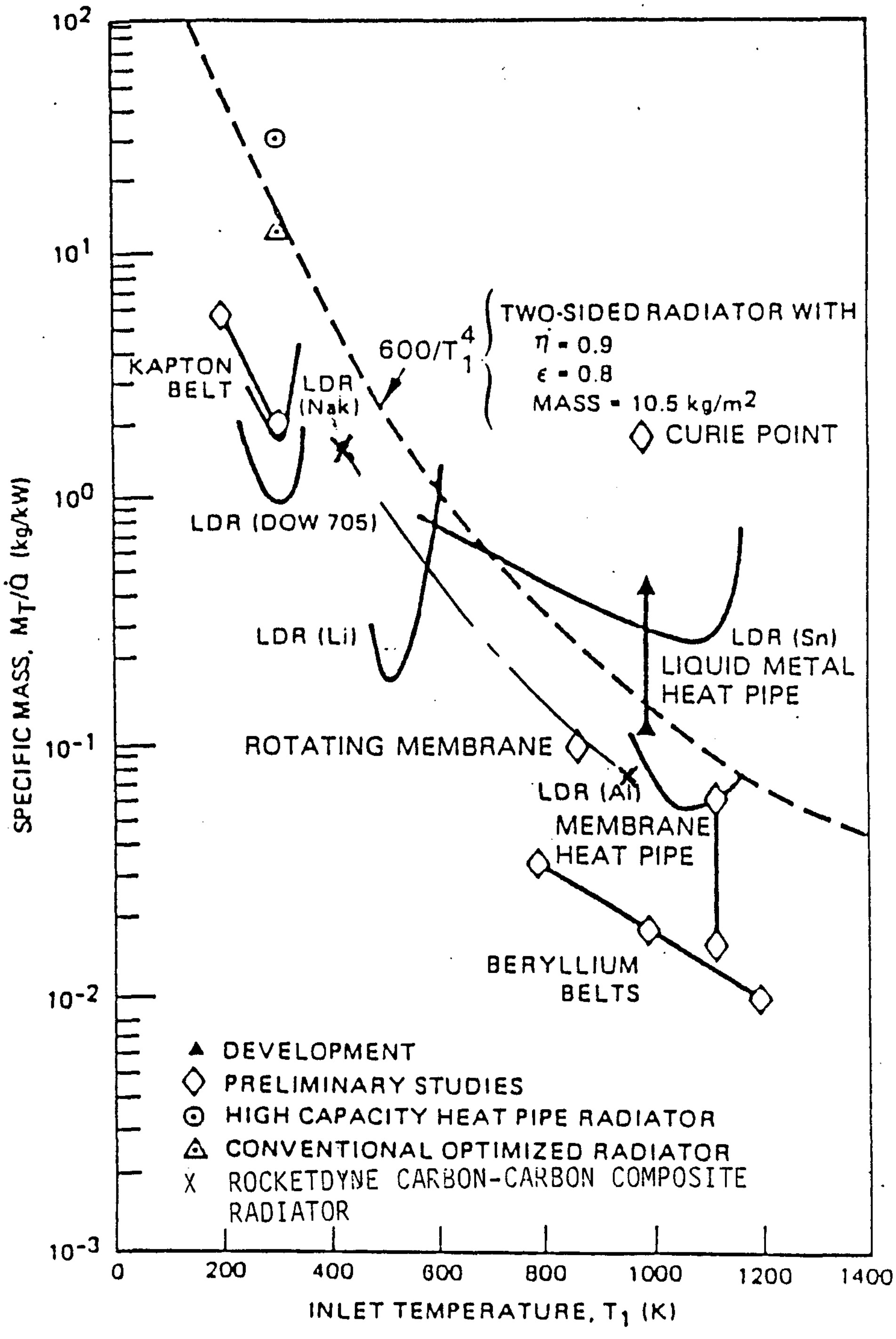


FIGURE 3.1.3.1-1

RADIATOR SPECIFIC MASS AS FUNCTION OF FLUID INLET TEMPERATURE

3.1.3.2 Carbon-Carbon Composite Components and Piping

All metals, even refractory alloys, lose creep strength with increases in operating temperature. Non-metallic compounds for high-temperature structural applications have been investigated by government laboratories and private industries through the last decade. Carbon-bonded carbon fiber materials have shown themselves to be the most promising of these new materials for aerospace applications. Figure 3.1.3.2-1 illustrates the strength to mass ratio for several more common metals and carbon-carbon as a function of temperature. For temperatures above 1000K, only silica/silica has a comparable strength to mass ratio with that of carbon-carbon.

Tests performed at Rocketdyne have shown that carbon-carbon requires a compatibility coating when used with liquid metals such as lithium and potassium at high operating temperatures. Research and development efforts are underway at Rocketdyne in several aerospace programs, such as NASP, MMW, SP-100 and Advanced Radiators, to develop compatibility coatings for carbon-carbon composite structures for use in high-temperature liquid metal environments. With a density of only 1.8 gm/cm^3 carbon-carbon composite could be substituted for refractory alloys (T-111, ASTAR-811C and Nb-1Zr) in the primary lithium loop piping and components, the boiler/reheater structure, and the PCS potassium vapor and liquid piping and components. System mass savings of 3000 Kg could be achieved in the 10 MWe system and a savings of 20,000 Kg is possible in the 200 MWe system using this emerging aerospace materials technology.

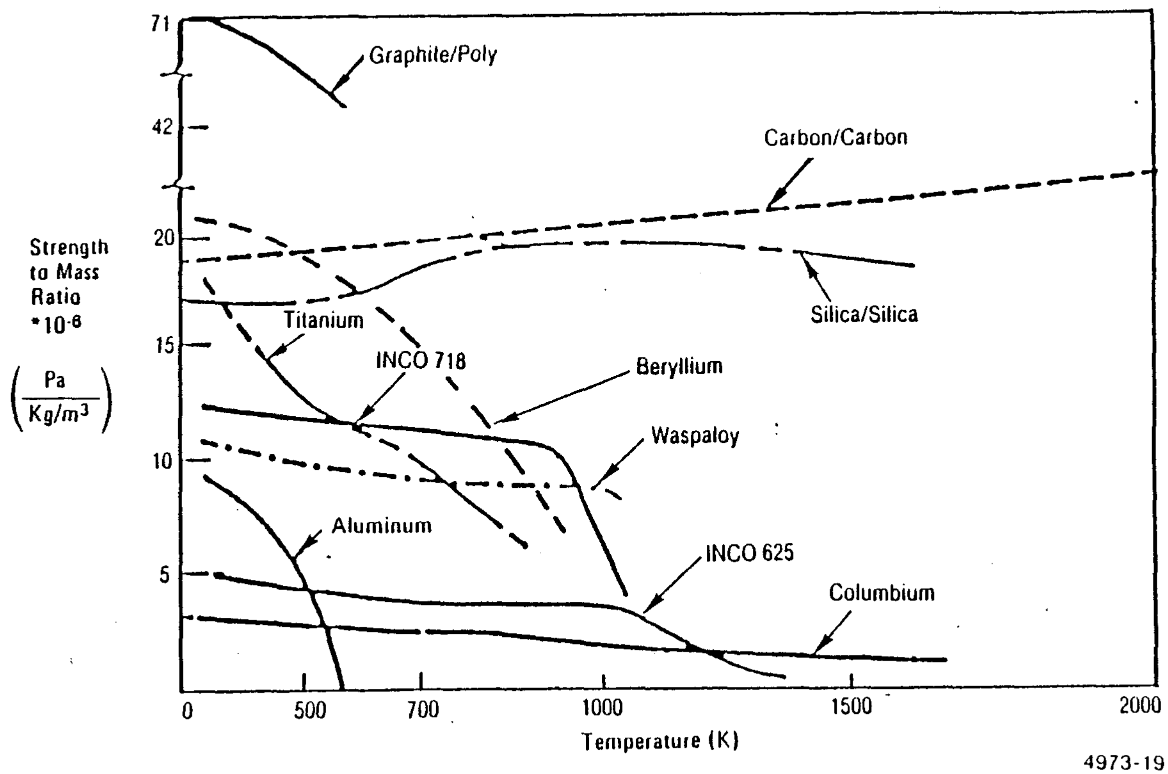


FIGURE 3.1.3.2-1
MATERIAL STRENGTH TO MASS RATIO AS A FUNCTION OF TEMPERATURE

3.1.3.3 Ceramic Turbine Materials

Typical long life turbine geometry is limited by allowable tip speed (259 m/sec) to avoid turbine erosion. Tip speed increases can be achieved by unique erosion resistant airfoil design. Rocketdyne has baselined 366 m/sec as an achievable, erosion free, limit based upon previous turbine erosion studies.

Refractory alloys were selected for the turbine because of their high strengths in high temperature potassium. Turbine mass, however, is driven by the high density refractory alloy selection. Ceramic turbine components have been successfully demonstrated by the airbreathing engine industry and can potentially be utilized by the potassium Rankine cycle turbines if compatibility and fatigue life can be demonstrated. The low density of ceramics offer significant potential for turbine mass reductions. Current studies indicate silicon nitride (Si_3N_4) may be a suitable turbine material. Total system mass reductions of 1480 and 18800 Kg could be achieved by using silicon nitride for turbine components.

3.2 Power System Configuration

The overall configuration of the 10MWe and 200MWe systems are shown in Figures 3.2-1 and 3.2-2. The reactor/shield are located at the top. The dose plane was taken as 100m for the 10MWe system and was set by the total radiator area required, i.e., 344m for the 200MWe system. The equipment is arranged below the reactor within a 17-1/2 degree angle on each side to prevent neutron scatter to the payload. Flat plate heat pipe radiators are arranged below the PCS equipment. Heat rejection radiators are provided for auxiliary loops, power conditioning rectifier cooling and the alternator cooling loops above the main cycle radiator. A realistic heat pipe length limit of 15m requires that three condenser/heat pipe radiator modules in parallel be employed for the 200MWe system to minimize the overall length within the shield angle. A lightweight rectangular structure of tubular pipe construction provides support for the equipment and an attachment to the payload and electrical propulsion system.

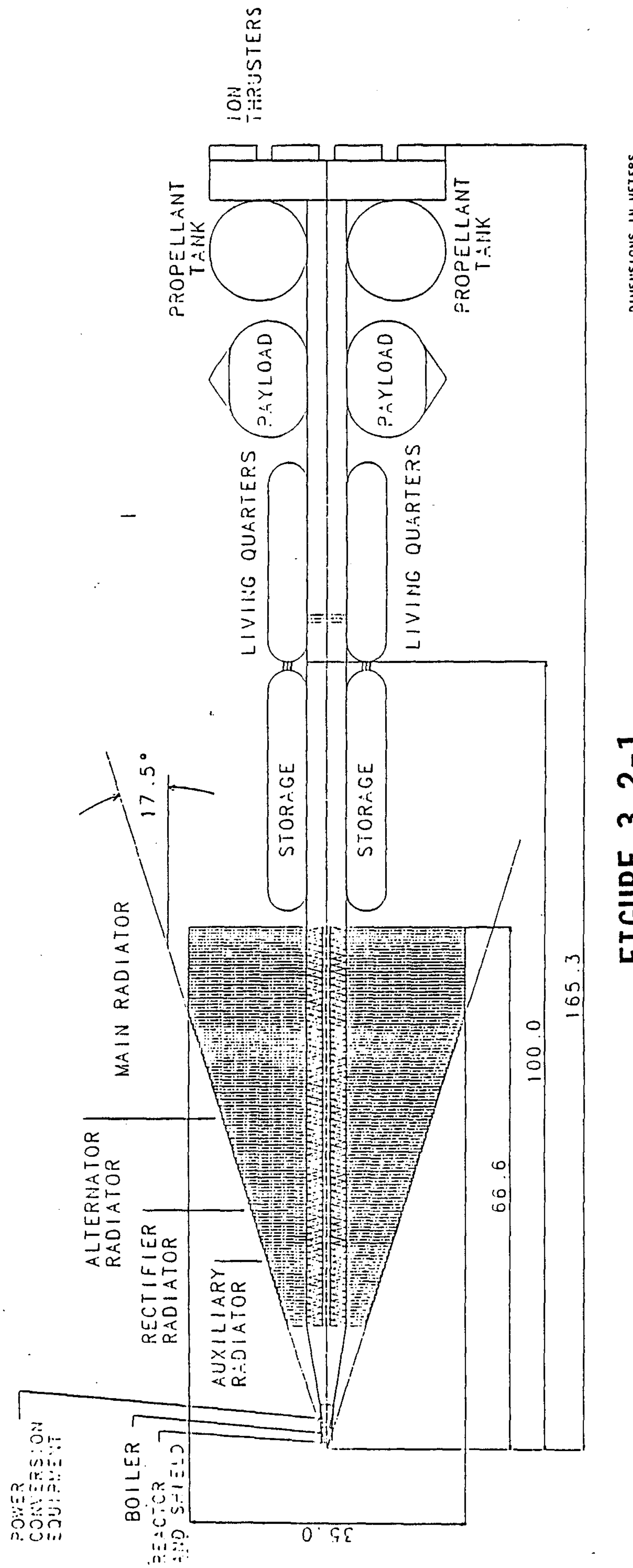


FIGURE 3.2-1
10 MWe VEHICLE CONFIGURATION

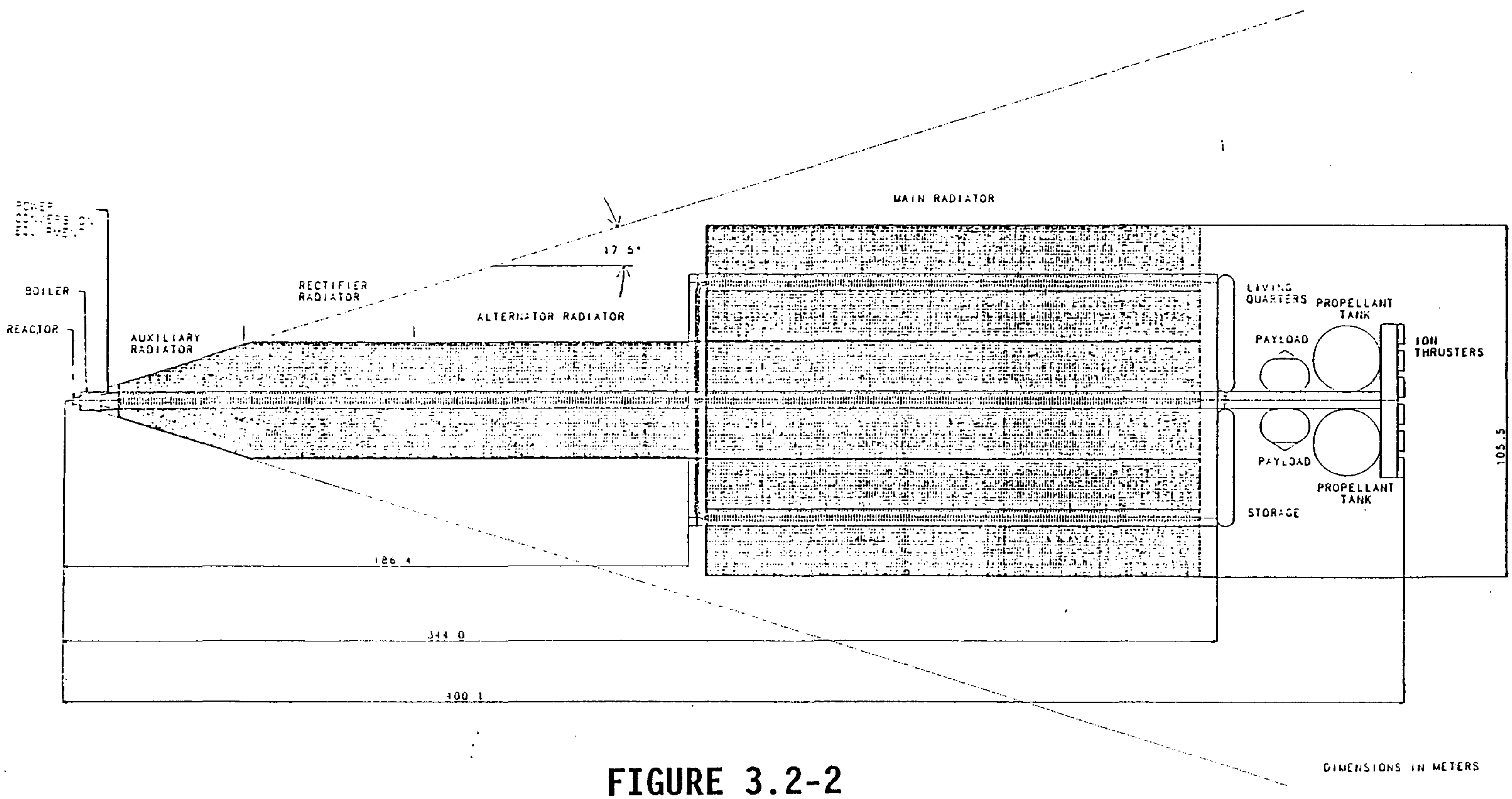


FIGURE 3.2-2
200 MWe VEHICLE CONFIGURATION

3.3 Power System Design

The overall power system consists of the Reactor/Primary Loop System, the Power Conversion System, Heat Rejection System and the Power Conditioning System.

3.3.1 Reactor/Primary Loop Subsystem

This system includes the reactor and shield and the lithium primary heat transport loop.

3.3.1.1 Reactor and Shield

The reactor is a lithium cooled fast reactor. Two fuel forms were considered for the reactor; cylindrical UN fuel pellets sealed inside thin-walled metal tubes similar to SP-100, and hexagonal cermet UN-W/25Re fuel under development for the MMW program (ref. 1). The monolithic cermet fuel form consisting of 100μm UN particles in a matrix of W-25Re alloy was selected.

The considerations that led to the selection of the cermet fuel form are summarized in Table 3.3.1.1-1. These were subdivided according to those related to safety and those related to performance. As may be seen, the cermet fuel is a clear winner. It is superior to pin-type cores in almost every category. Its high strength, and high thermal conductivity lead to low gradients and good thermal shock resistance, and the solid block form of the fuel element makes the core very resistant to core compaction type accidents. Thus the cermet fuel provides an exceptionally safe core both mechanically and neutronically.

It must be recognized that there is more experience with pin-type elements and that this is the form chosen for SP-100. However the 1350K reactor outlet temperature and operational requirements of SP-100 are much less severe than those required for these systems and a new pin type fuel element with a different cladding would have to be developed for the higher 1550K reactor outlet temperature required for these systems. The cermet fuel element is clearly the proper selection for this higher temperature application and the relative risk associated with its development versus development of a higher temperature pin type element is minimal.

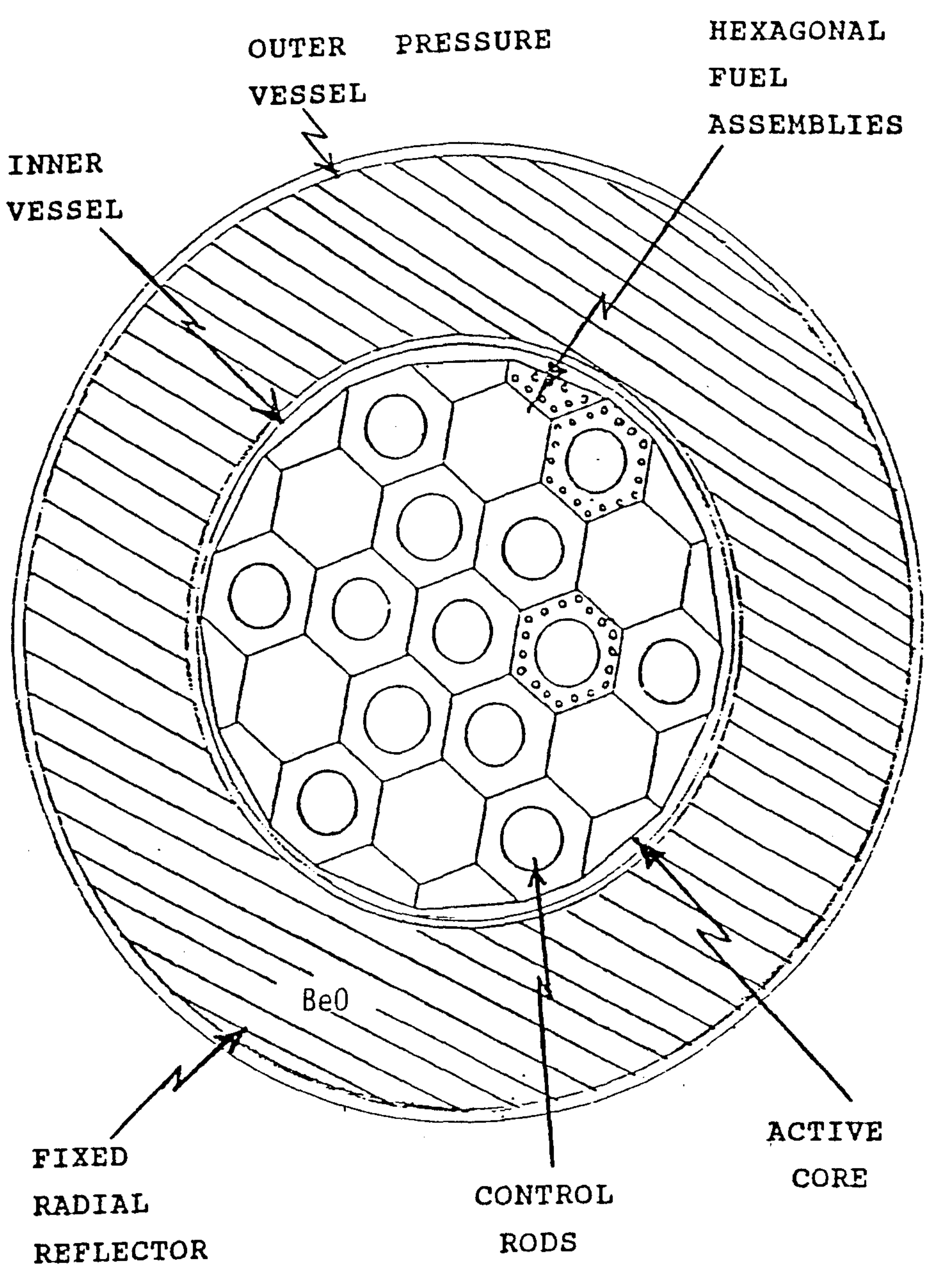
A typical reactor cross section is shown in Figure 3.3.1.1-1. The fuel elements are hexagonal blocks with 0.564cm internal cylindrical coolant flow channels lined with W-25Re. Some elements have a large central hole to accommodate insertion of control or safety rods. The lithium coolant flows upward through the core and fixed radial reflector into an upper plenum. The outlet coolant is channeled from this plenum to the boiler by twelve small pipes in grooves located around the perimeter of the shield. The L/D of the active core is 1.11. The active core is surrounded by a BeO reflector inside the reactor vessel. The peak fuel burnup is 25% of the uranium in the fuel and the peak fuel temperature is 1820K.

Ref. 1. Battelle PNL, PNL 6744, Multimegawatt Fuels Development, FY 1988 Status Report, May, 1989

Table 3.3.1.1-1 Comparison of Cermet and Pin-Type Fuels

Consideration	Favors	Reason
<u>Safety</u>		
Water subcriticality	Cermet	Smaller coolant fraction, Re spectral shift
Core compaction	Cermet	Higher strength, block fuel form
Lattice expansion and flooding	Cermet	Not possible with cermets
Fuel element bowing	Cermet	More rigid elements
Loss of coolant accident	Cermet	Better heat conduction
Transient overpower events	Cermet	Lower fuel temperature
Fuel (cladding) failure	Cermet	Fission gas contained in cermet matrix - No clad to fail, no fission gas plenum or venting required
<u>Performance</u>		
Burnup potential	Cermet	Higher strength
Fuel temperature	Cermet	Lower ΔT in cermet fuel
Load following	Cermet	Faster ramp capability - reduced fuel/clad mechanical interaction
Reactivity feedback coefficients	Cermet	Faster thermal expansion
Fuel fraction	Equal	
Reactor size	Cermet	More compact due to higher burnup—no gas plenum
Reactor mass	Cermet	More compact
Data base	Pins	More pins have been irradiated (but at lower temperature and burnup)

FIGURE 3.3.1.1-1
REACTOR CROSS SECTION



REACTOR PARAMETERS FOR SPECIFIC MISSIONS

POWER (MWE)	10	10	200	200
POWER (MWT)	52	49	1045	989
LIFETIME (YR)	2	10	2	10
ACTIVE CORE O.D. (CM)	39.0	66.7	106	181
RADIAL REFLECTOR THICKNESS (CM)	14.2	14.2	14.2	14.2
PRIMARY CONTROL RODS (NO.)	7	7	7	7
SECONDARY SHUTDOWN RODS (NO.)	6	6	6	6

At these large power levels and long mission lifetimes, it is no longer possible to provide all the reactor control requirements with external reflector control. A 10 MWe system reactor could only use reflector drum control for a lifetime of one year or less. The 10 MWe reactor could employ a sliding external reflector control system for lifetimes out to about 2-3 years. For significantly higher power levels or longer lifetimes, active in core control rods are required. Even though sliding external reflector control could have been employed for the 10 MWe, two-year application, all four systems developed in this study employ a fixed internal reflector with all the control being provided by in-core active control rods. There are seven in-core operational control and six in-core reactor shutdown rods. The operational control rods must be cooled by the lithium reactor coolant and, therefore, require vessel seal arrangements. The shutdown rods do not require active cooling and therefore are simply inserted into thimbles without the need for seals. The operational control rods also serve as a backup reactor shutdown system.

The man-rated dose criteria used for radiation shielding is a 5 rem/year contribution at the dose plane from the reactor. A minimum reactor/payload separation distance of 100m was taken for the 10MWe system. A 344m separation distance for the 200MWe system was set from radiator integration considerations. A shadow shield with a shield cone half-angle of 17.5 degrees is used for all the systems. The shield is made up of alternate layers of tungsten and Be_2C with 5 volume percent B_4C. Be_2C is employed rather than LiH because even though it results in a heavier shield, it is a high temperature material which can reject its heat directly to space without the need for an active cooling system. All primary and PCS equipment is arranged within the 17.5 degree cone half-angle for both cases.

The reactor/shield system masses are listed in Table 3.3.1.1-1. It can be seen that the reactor weight is approximately proportional to lifetime due to the 25% fuel burnup limit in each case. The estimated shield geometry and thicknesses for the four systems is shown in Figure 3.3.1.1-2. The boiler provides significant radiation shielding for the reactor. The 10 MWe systems have much smaller boilers to aid in the shielding and, therefore, require thicker shields. The 10 MWe systems employ two alternating layers of tungston and Be_2C/B_4C, whereas the 200 MWe systems only employ one of each. The increased shield weight for the ten-year 10 MWe mission is caused by the increased diameter of the larger 10-year reactor. For the 200 MWe system the ten-year shield mass is less than the two-year shield. This is because the neutron and gamma ray axial leakage from the ten-year reactor is lower due to its larger size; in addition, the boiler for the ten-year reactor is 20% larger than the boiler for the two-year reactor (boiler designed for 5 PCS's instead of 4).

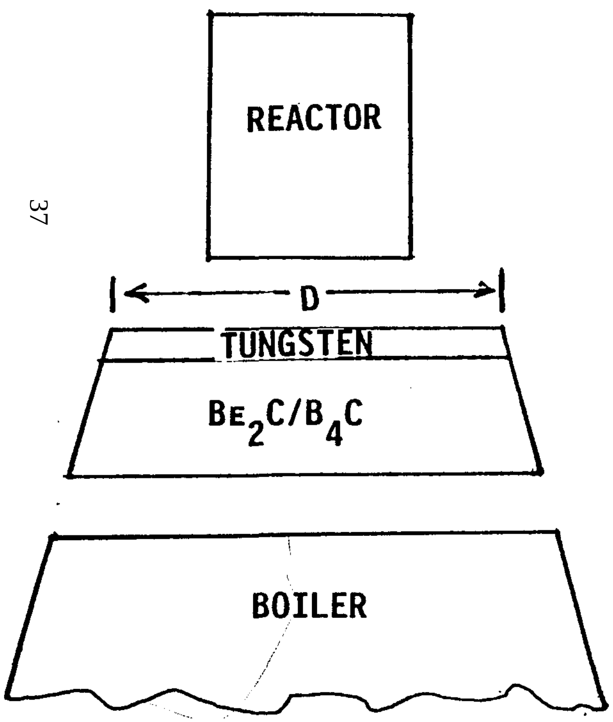
The shielding provided by the boiler is extremely important, especially for the 200 MWe systems. The mass of the boiler is in excess of 90,000 Kg. It was estimated that if the boilers are not used as a shield, the shield mass required will be approximately 47,400 Kg and 60,200 Kg for the two-year and ten-year reactors, respectively. The shielding provided by PCS equipment other than the boiler, e.g., turboalternators, pumps, etc., has not been included in the analyses. By strategically locating these below

TABLE 3.3.1.1-1
REACTOR/SHIELD SYSTEM MASS

POWER (MWE)	10	10	200	200
LIFETIME (YEARS)	2	10	2	10
MASS (KG):				
REACTOR	1,683	4,500	13,677	59,133
SHIELD	4,150	6,930	14,700	13,000
TOTALS	5,833	11,430	28,377	72,133

FIGURE 3.3.1.1-2

RADIATION SHIELD CONFIGURATIONS



SHIELD DIMENSIONS

	10 MWE		200 MWE	
	2 YR	10 YR	2 YR	10 YR
DIAMETER (CM)	152.4	199.2	380	440
TOTAL THICKNESS (CM)				
W	8.2*	8.2*	4.4	3.0
BE_2C/B_4C	62.6*	63.1*	22.0	13.9
MASS (KG)	4150	6930	14700	13000

*INCLUDES TWO ALTERNATING LAYERS OF EACH MATERIAL the boiler, they could further reduce the dose rate by up to a factor of 5 (from 5 Rem/yr down to 1 Rem/yr).

3.3.1.2 Primary Heat Transport

A pumped-lithium primary loop extracts thermal energy from the reactor and transports it to the potassium boiler which serves as the heat source for the power conversion cycle. The primary loop schematic and requirements are shown in Figure 3.3.1.2-1. Two ac electromagnetic (EM) induction pumps connected in series provide the lithium loop hydraulic head. A decay heat removal jet pump assembly provides a diverse and redundant method for reactor decay heat removal to meet system safety requirements. A noncondensible gas control assembly, located in the decay heat removal branch line, removes any helium gas bubbles formed in the reactor from the lithium side stream. A liquid metal expansion compensator accommodates thermal expansion of the lithium in the primary system piping during startup and thermal transient events and maintains system pressure. The entire primary heat transport loop is electrical trace heated to facilitate loop thaw-out during the initial system startup.

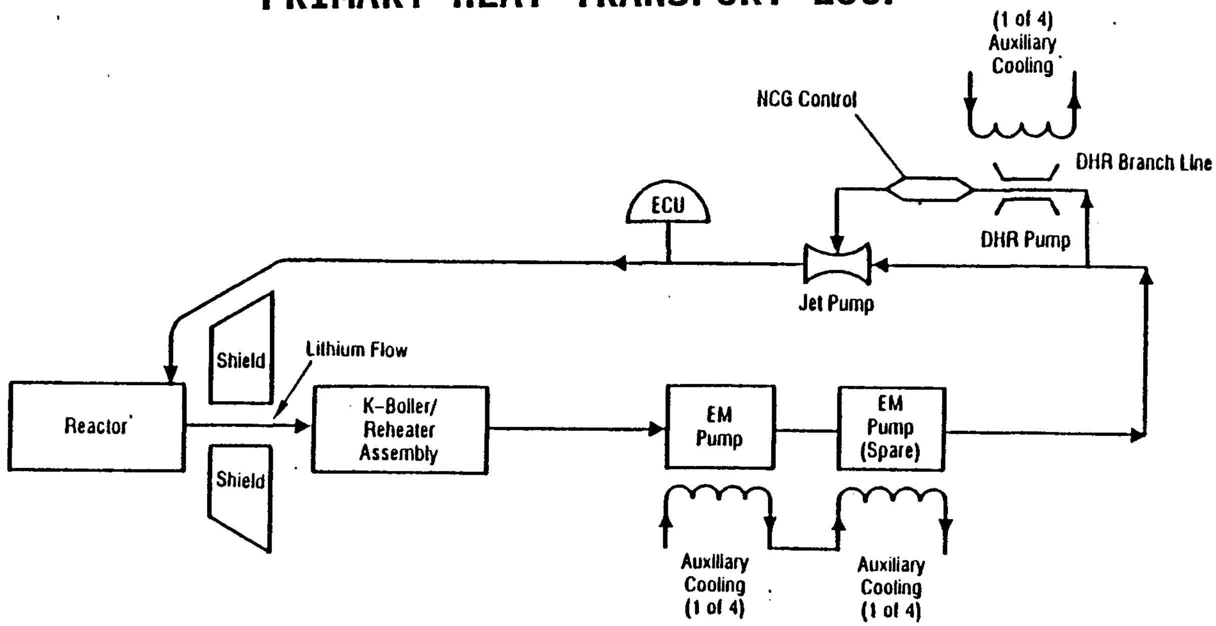
The primary lithium pump shown in Figure 3.3.1.2-2 is a four pole, three phase ac annular linear induction pump. This design incorporates electrical trace heaters to melt out the lithium in the pump throat prior to pump startup. The auxiliary cooling subsystem provides coolant flow to the EM pump stator and central torpedo regions to limit the peak temperature of the magnetic materials to less than 1100K.

The decay heat removal (DHR) requirements are listed in Table 3.3.1.2-1. The DHR function within the PHTS is diverse and redundant to the primary heat transport circuit. A schematic showing these functions is presented in Figure 3.3.1.2-3. The primary lithium pumps are powered from redundant electrical buses supplied by battery power. The DHR pump design must operate independent of this power supply. An integral thermoelectric electromagnetic (TEM) dc conduction pump design was selected to meet this requirement. To reduce the volumetric flow rate through the DHR pump throat, the pump is located on a small branch line of the main lithium line. The jet pump is designed to couple the output flow of the DHR pump with the main lithium line flow. During normal operations the jet pump provides a net zero head. However, on loss of the main pumps, the jet pumps provide sufficient main loop flow for decay heat removal. Multiple TEM pumps are plumbed in parallel to meet the DHR flow requirements.

Table 3.3.1.2-2 provides the mass breakdown for the primary heat transport system.

FIGURE 3.3.1.2-1

PRIMARY HEAT TRANSPORT LOOP



REQUIREMENTS	10MWE	200MWE
THERMAL CAPACITY (MWT)	49.1	989.
NET HEAD (KPA/PSID)	115/16.6	317/46
FLOW RATE (KG/S/GPM)	117/4358	2353/87,730
PRIMARY LINE DIA. (M)	0.241	0.851
BRANCH LINE DIA. (M)	0.102	0.135 (6 LINES)

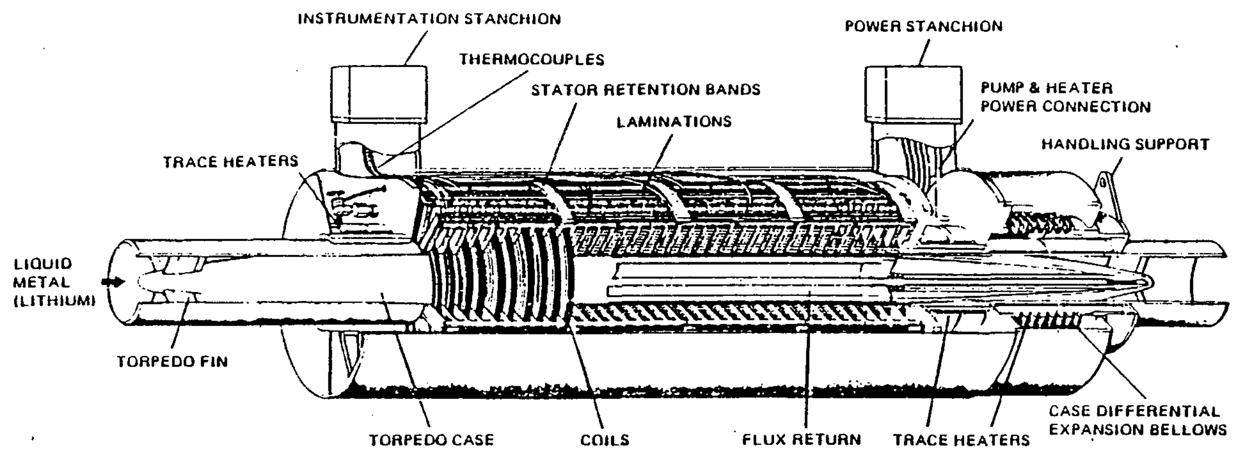
TABLE 3.3.1.2-1

DECAY HEAT REMOVAL/JET PUMP ASSEMBLY REQUIREMENTS

- A DIVERSE AND REDUNDANT MEANS OF REMOVING REACTOR DECAY HEAT FOLLOWING SYSTEM SHUTDOWN SHALL BE PROVIDED

DHR PARAMETER	10MWE	200MWE
MINIMUM REACTOR FLOW RATE (KG/S)	5.8	118.
TEM PUMP MASS FLOW (KG/S)	7.7	10
TEM PUMP NET HEAD (KPA)	20	30
PUMP THERMAL POWER (KWT)	75	150
NO. OF TEM PUMPS	2	8

FIGURE 3.3.1.2-2
PRIMARY HEAT TRANSFER SYSTEM LITHIUM PUMP DESIGN



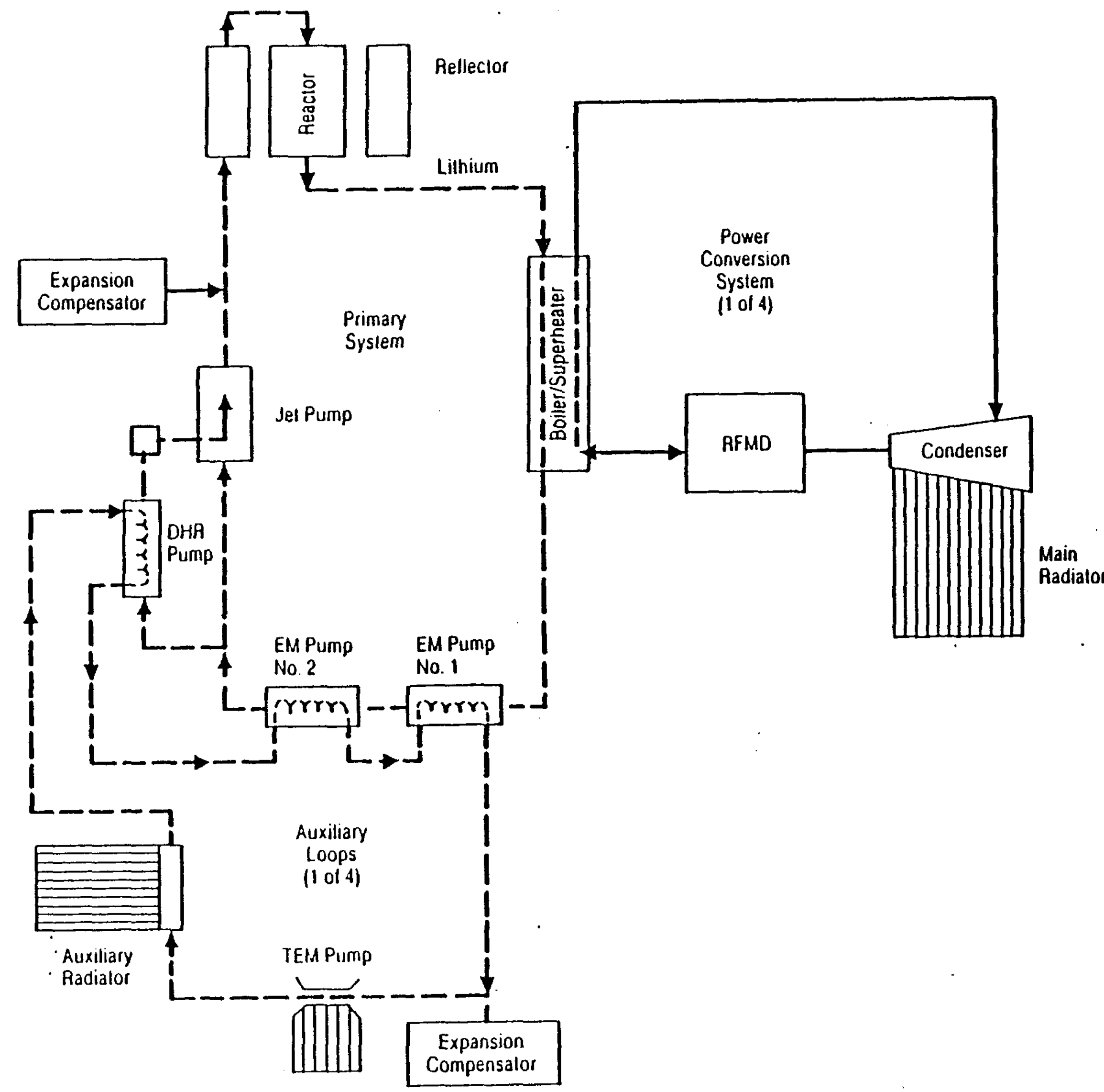
DESCRIPTION	10MWE	200MWE
MASS (KG)	1035	29,775
EFFICIENCY (%)	18.6	33.2
INPUT POWER (KWE)	18.7	5,820
NO. POLES	4	4
NO. PHASES	3	3
TERMINAL VOLTAGE (V.)	470	4,700
FREQUENCY (Hz)	68	30
LENGTH (M)	1.6	3.7
DIAMETER (M)	0.65	2.0

TABLE 3.3.1.2-2
PRIMARY HEAT TRANSPORT MASS SUMMARY

COMPONENTS	10MWE	200MWE
TWO PRIMARY EM PUMPS	2,070	59,550
DHR/JET PUMP/NCG CONTROL ASSEMBLY(S)	132	1,030
ELECTRICAL HEATERS	60	220
EXPANSION COMPENSATOR(S)	550	7,700
LITHIUM PIPING	670	9,500
LITHIUM INVENTORY	1,600	22,500
TOTAL SUBSYSTEM MASS (KG)	5,082	100,500

FIGURE 3.3.1.2-3

Decay Heat Removal



3.3.1.3 Auxiliary Cooling

Auxiliary Cooling Loops

The auxiliary cooling loops (ACL) provide cooling to various PHTS and PCS components during normal operation. They also provide a redundant and diverse pathway for reactor decay heat removal (DHR) following system shutdown.

The ACL consists of self-regulated and self-powered pumped lithium heat transport loops, one per PCS loop, plumbed in parallel for the PHTS component cooling. Each of the ACL loops acts as a self-regulating thermal bus that is independent of the system electrical power source. There are no moving parts and all of the components are based upon a proven technology base (SNAP-10A).

The ACL provides a decay heat removal pathway in parallel with the main heat transport pathway to the condenser as was shown in Figure 3.3.1.2-3. The ACL provides 540 kWt of heat rejection capacity to the PHTS and reactor components for the 10MWe system and 6200 KWt for the 200MWe system. The ACL provides sufficient capacity to handle the entire DHR function for a reactor trip. In the event of a reactor trip from full power operation, decay heat is initially dumped to the boiler/condenser pathway in addition to the ACL loops.

Table 3.3.1.3-1 shows the ACL thermal loads for the reactor, PHTS, and PCS components. Three of the four (or five for 10-year missions) ACL loops are designed to provide the full cooling capacity required by the system. The fourth (and fifth) ACL loops are provided for redundancy. The auxiliary loops supply thermal conditioning to the standby backup PCS loop components during normal operation. A single auxiliary cooling radiator rejects the waste heat from all the auxiliary loops to space.

The mass breakdown for the ACL is provided in Table 3.3.1.3-2. The weight provided includes 4 loops for the 2-year mission and 5 loops for the 10-year mission.

Alternator Cooling Loops

Each operating alternator in the PCS requires cooling of its stator and rotor to remove waste heat and limit the temperature in these regions to less than 530K. The amount of waste heat to be removed from each alternator is the product of its rated output and inefficiency. The requirements for the alternator cooling loops are listed in Table 3.3.1.3-3. Pumped liquid-potassium coolant loops were selected based upon the compatibility with the potassium working fluid used in the turboalternator bearing supply system. A schematic for this system is shown in Figure 3.3.1.3-1. Each alternator is designed with its own dedicated coolant loop which is powered by a centrifugal pump located on the alternator shaft. The transport piping from each alternator coolant loop is manifolded together with the other alternator loops in the PCS and the heat is rejected by a common heat pipe radiator.

TABLE 3.3.1.3-1
AUXILIARY COOLING LOOPS
THERMAL LOADS

		ACTIVE UNITS	THERMAL LOADS (KWT)	
SUBSYSTEM	COMPONENT	10MWE/200MWE	10MWE	200MWE
PHTS	PRIMARY EM PUMPS (LI)	2	264	4,300
PCS	RFMD	3/9	16	520
PCS	PCS BEARING SUPPLY	(8 X 3)	70	120
PHTS	DHR TEM PUMP	1/8	150	1,200
REACTOR	CONTROL ACTUATORS	13	40	60
TOTAL (OF THREE LOOPS)			540	6,200

TABLE 3.3.1.3-2
AUXILIARY COOLING LOOPS
MASS BREAKDOWN

MASS (KG)

COMPONENT	10MWE/2YR	10MWE/10YR	200MWE/2YR	200MWE/10YR
ELECTRICAL HEATERS	10	12	30	35
MANIFOLD	30	38	120	150
LITHIUM INVENTORY	108	135	450	560
THERMOELECTRIC PUMPS	76	95	300	375
ACCUMULATORS	80	100	320	400
PIPING	120	150	500	625
TOTAL SUBSYSTEM MASS (ALL LOOPS)	424	530	1,720	2,145

FIGURE 3.3.1.3-1
PCS ALTERNATOR COOLANT LOOP LAYOUT

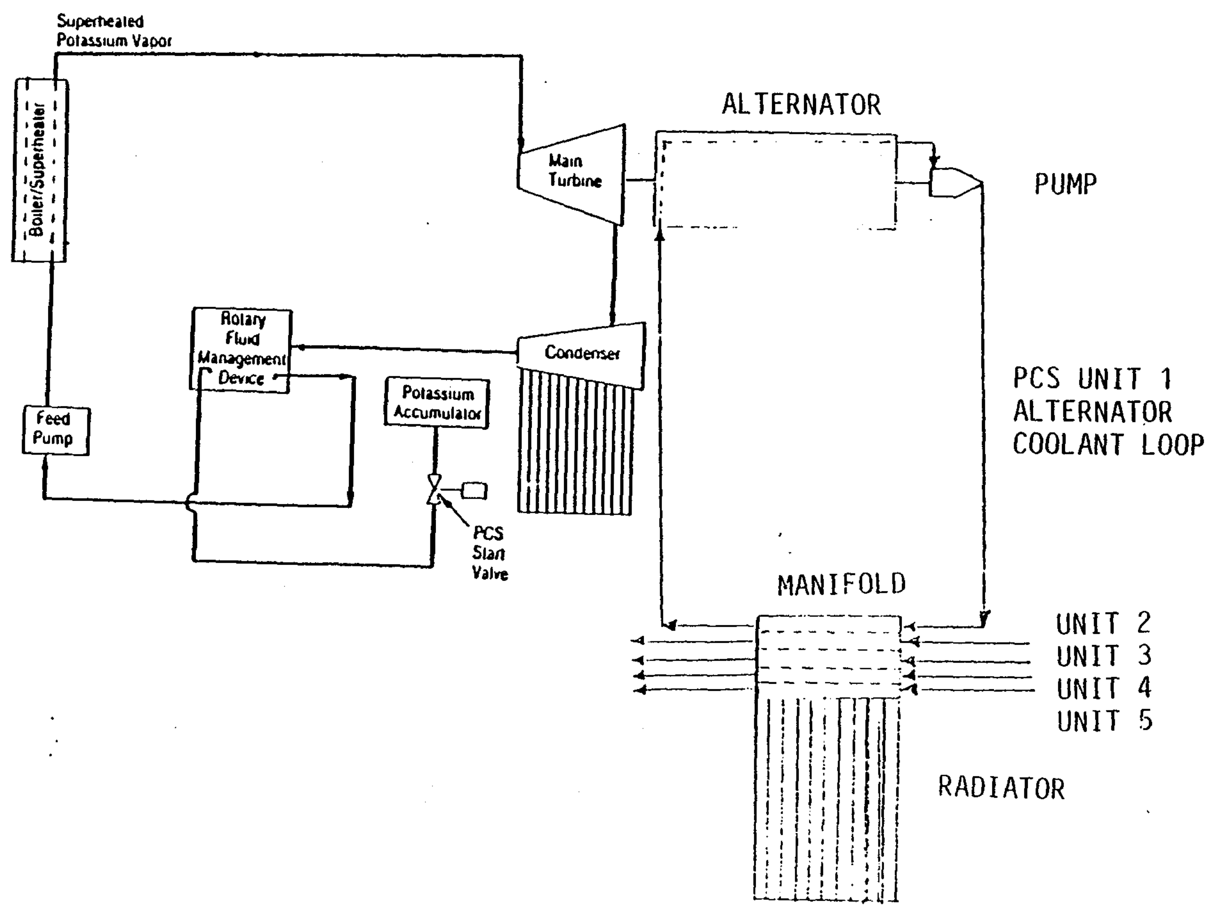


TABLE 3.3.1.3-3
ALTERNATOR COOLANT LOOP REQUIREMENTS
PER ALTERNATOR

ALTERNATOR PARAMETER	$10MW_E$ SYSTEM	$200MW_E$ SYSTEM
THERMAL POWER (KW_T)	141	1750
COOLANT MASS FLOW (KG/S)	6.4	79
NET PUMP HEAD (KPA)	435	690
SHAFT POWER (KW_S)	5.9	115
TRANSPORT PIPE DIA (M)	.05	.18

A mass breakdown for the alternator cooling loops is listed in Table 3.3.1.3-4 per power conversion system. The total system weight is also presented for the two- and ten-year missions.

TABLE 3.3.1.3-4
PCS ALTERNATOR COOLANT LOOP MASS BREAKDOWN

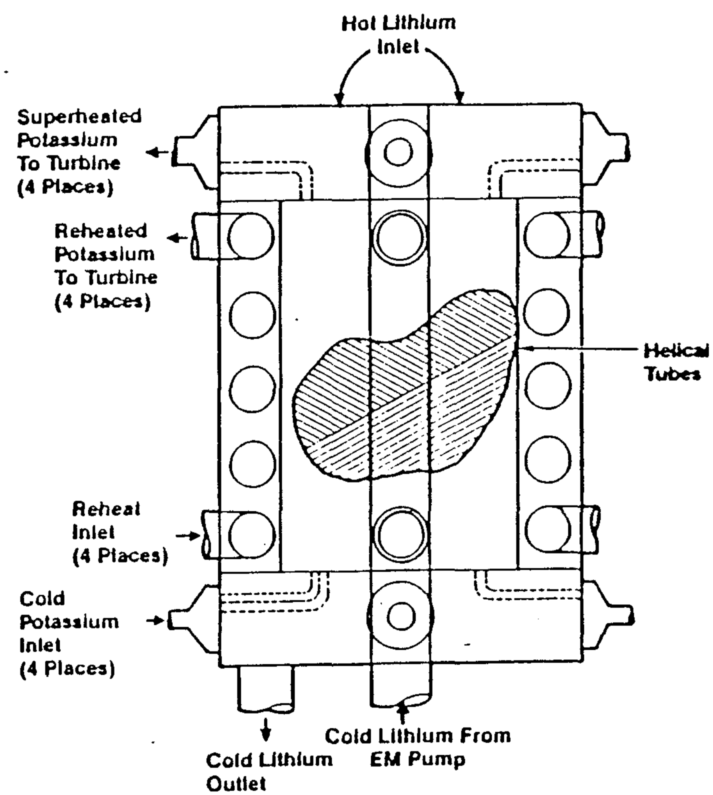
COMPONENT	MASS (KG) 10MWE SYSTEM	200MWE SYSTEM
ELECTRICAL HEATERS	6	20
CENTRIFUGAL PUMP	7	25
EXPANSION COMPENSATOR	21	200
POTASSIUM INVENTORY	66	820
PIPING	18	135
SUBTOTAL/ALTERNATOR	118	1,200
TOTAL SYSTEM WEIGHT		
2 YEAR MISSION (4)	472	4,800
10 YEAR MISSION (5)	590	6,000

3.3.1.4 Boiler/Reheater

The boiler transfers heat from the reactor lithium coolant to the potassium working fluid. In addition to providing superheated potassium to the turbines, it is also employed to reheat to the moist vapor stream exiting the high pressure stages of the turbine to provide a slightly superheated stream entering the low pressure stages of the turbine. The helical tube boiler is similar in concept to the Superphenix liquid metal steam generator design. The helical tubes accommodate tube-to-tube and tube-to-shell differential expansions. The helical design provides for a compact, low mass heat exchanger. The boiler/reheater configuration, along with its heat transfer requirements and dimensions, is shown in Figure 3.3.1.4-1 for both the 10MWe and 200MWe systems. Although the boiler configuration is shown as cylindrical in Figure 3.3.1.4-1, it will be conically configured to provide maximum radiation shielding benefits. For both power levels three active units are employed. Double walled tubes are employed to prevent a single point failure to the primary system. An extra set of tubes for a single nonactive backup PCS unit are provided for the two-year mission and two sets are provided for the ten-year mission.

The boiler/reheater concept uses a common lithium shell side with all of the potassium power conversion units on the tube side. This eliminates the need for high temperature lithium bypass valves that would be required if multiple boilers were provided. The hot lithium coolant leaving the reactor core passes through boiler inlet manifold and into the shell side of the boiler. The boiler shell side has an annular geometry, providing for the lithium coolant return line to the reactor through the center of the annulus. The lithium flow is one pass on the shell side with cross flow baffles provided to ensure proper distribution of the lithium. The boiler tube side provides for once through boiling and superheating of the potassium. Boiling heat transfer in the boiler is enhanced by using twisted tape inserts in the boiler tubes. This will provide for stable boiling and minimize liquid droplet carry-over in a microgravity environment.

FIGURE 3.3.1.4-1
POTASSIUM BOILER/REHEATER



TYPICAL 3+1 CONFIGURATION

Boiler Configuration

- Common Lithium Shell Side
- Integral Boiler-Reheater
- Once Through Potassium Boiling
- Helical Tube Design

<u>10 MWe Requirements</u>

- Heat Duty	51 MWt
- Lithium	123 kg/s
- Potassium Flow	23 kg/s

10 MWe Sizes	2 Year (3+1)	10 Year (3+2)
- Tube size	1.9 cm	1.9 cm
- No. of Tubes	332	390
- Boiler Height	2.7 m	2.9 m
- Boiler Diameter	1.5 m	1.6 m
- Weight (wet)	4600 kg	5500 kg

<u>200 MWe Requirements</u>

- Heat Duty	972 MWt
- Lithium Flow	2486 kg/s
- Potassium Flow	470 kg/s

200 MWe Sizes	2 Year (3+1)	10 Year (3+2)
- Tube size	3.8 cm	3.8 cm
- No. of Tubes	1140	1325
- Boiler Height	7.0 m	7.5 m
- Boiler Diameter	5.2 m	5.6 m
- Weight (wet)	90000 kg	107600 kg

3.3.2 Power Conversion Subsystem

3.3.2.1 Turboalternator

Figure 3.3.2.1-1 shows the configuration of the turboalternator. The overall turboalternator dimensions and mass are given in Table 3.3.2.1-1. The turbine and alternator are treated sequentially in the following sections.

Turbine The turbine requirements for the 10 MWe and 200 MWe systems are given in Tables 3.3.2.1-2 and 3.3.2.1-3. These reflect the lower optimum condensing temperature and pressure for the 10-year missions. Figure 3.3.2.1-2 shows the turbine configuration, and the characteristics of the turbine designs are presented in Tables 3.3.2.1-4 and 3.3.2.1-5. The turbine employs eight reaction stages. The eight stages are divided into four high-pressure and four low-pressure stages on the same shaft. Vapor reheat is employed to maintain the minimum vapor quality limits within the turbine. The turbine is designed for high reliability. It employs a maximum tip speed of 366 m/s (1220 ft/s), a 90% minimum turbine vapor quality and noncontacting seals and bearings. Stationary components are constructed of T-111 and rotating components are constructed of ASTAR 1511-C. The mass of only the turboalternator is also listed in the tables for each system.

Alternator The alternators for the two power levels are of the same design except for size, weight and rating. Table 3.3.2.1-6 presents the requirements for the alternator and Table 3.3.2.1-7 lists the configurational parameters. The alternator physical layout is shown in Figure 3.3.2.1-3.

The alternator output frequency is a function of the rotational speed of the machine and the number of magnetic poles designed into the machine. Each of these is determined during the machine design based on the strength of the rotor materials and the optimum magnetic design. The rotor speed has primarily been determined by the turbine design to obtain optimum overall performance between the turbine and alternator. Alternator output frequency is expected to be 460 hertz for the 10 Mw design and 180 hertz for the 200 Mw design, but will depend upon final alternator design.

The salient pole alternator provides the best combination of long life, reliability and performance for applications at these power levels. The integral exciter, salient pole machine provides reliable output voltage control without slip rings or brushes and is lighter in weight than homopolar induction type alternators. Salient pole machines, in this size range, can also provide the high voltage required to eliminate the need for a step up transformer in the power conditioning system.

Trade studies of high temperature (675 K) versus medium temperature alternator systems have indicated that the 425 to 455 K temperature range allows the use of reliable high voltage insulation and results in a lighter, more efficient alternator. These factors more than compensate for the increased weight of the thermal management system required for this temperature machine.

FIGURE 3.3.2.1-1

Turboalternator Design

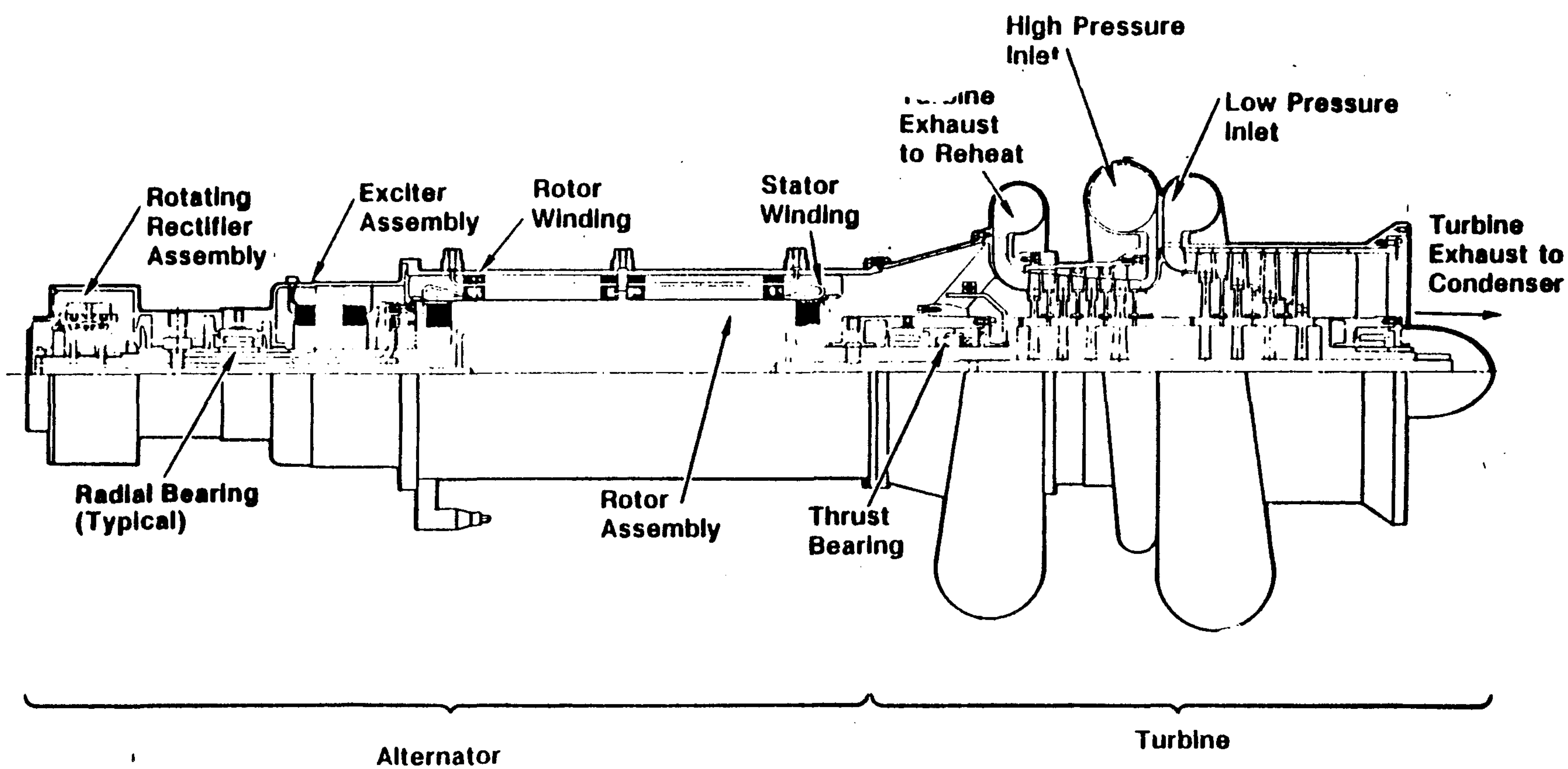


TABLE 3.3.2.1-1
TURBOALTERNATOR SIZE AND MASS

	10 MWE		200 MWE	
OVERALL DIMENSIONS, M				
LENGTH	2.0		6.9	
MAXIMUM DIAMETER	0.5		2.2	
MASS/TURBOALTERNATOR, KG				
TURBINE	463		5,870	
ALTERNATOR	744		8,295	
TURBOALTERNATOR	1,207		14,165	
	2 YR	10 YR	2 YR	10 YR
TOTAL TURBOALTERNATOR MASS/SYSTEM, KG	5,828	6,035	56,660	70,825

TABLE 3.3.2.1-2

TURBOALTERNATOR TURBINE
10 MW REQUIREMENTS

	2 YEAR LIFE		10 YEAR LIFE	
POWER	10.5 MW	(13,410 HP)	10.5 MW	(13,410 HP)
SPEED	1,466 RAD/S	(14,000 RPM)	1,466 RAD/S	(14,000 RPM)
DRIVE FLUID	POTASSIUM VAPOR			
INLET TEMPERATURE	1450 K	(2610 ^{o}R)	1450 K	(2610oR)
INLET PRESSURE	1239 K PA	(180 PSIA)	1239 K PA	(180 PSIA)
FLOW RATE	7.63 KG/S	(16.8 LB/S)	7.13 KG/S	(15.7 LB/S)
OUTLET TEMPERATURE	1025 K	(1845 ^{o}R)	1000 K	(1800oR)
OUTLET PRESSURE	96.5 K PA	(14 PSIA)	75.8 K PA	(11.0 PSIA)

TABLE 3.3.2.1-3

TURBOALTERNATOR TURBINE

200 MW Requirements

	2 Year Life		10 Year Life	
• Power	70.6 MW	(94,676 hp)	70.6 MW	(94,676 hp)
• Speed	367 rad/s	(3,500 rpm)	367 rad/s	(3,500 rpm)
• Drive Fluid	Potassium Vapor			
• Inlet temperature	1450 K	(2,610 ° R)	1450 K	(2610 °R)
• Inlet pressure	1239 k Pa	(180 psia)	1239 k Pa	(180 psia)
• Flow rate	154 kg/s	(340 lb/s)	143 kg/s	(315 lb/s)
• Outlet temperature	1025 K	(1845 ° R)	1000 K	(1800 °R)
• Outlet pressure	96.5 k Pa	(14 psia)	75.8 k Pa	(11.0 psia)

FIGURE 3.3.2.1-2

Turboalterator Turbine Configuration

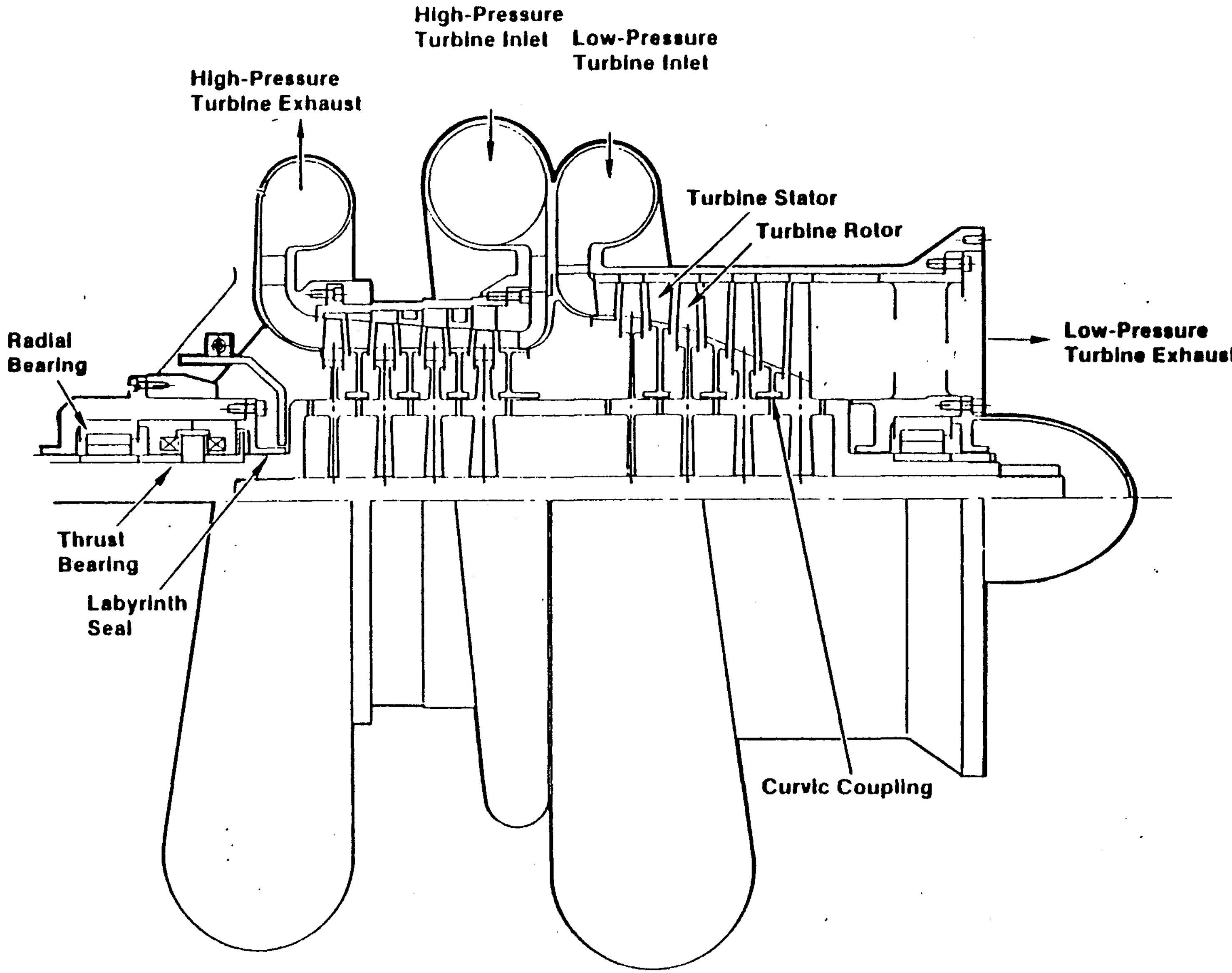


TABLE 3.3.2.1-4
TURBOALTERNATOR TURBINE
10 MW DESIGN

	2 YEAR LIFE		10 YEAR LIFE	
• 8 STAGE REACTION TURBINE				
MATRIALS	T-111 & ASTAR 1511C		T-111 & ASTAR 1511C	
WEIGHT (TURBINE ONLY)	463 KG	(1020 LB)	463 KG	(1020 LB)
• HIGH PRESSURE TURBINE				
POWER	1563 kW	(2096 HP)	1560 kW	(2092 HP)
SPEED	1466 RAD/S	(14000 RPM)	1466 RAD/S	(14000 RPM)
NUMBER OF STAGES	4		4	
PRESSURE RATIO	2.9		3.2	
INLET TEMPERATURE	1450 K	(2610 ^{O}R)	1450 K	(2610 ^{O}R)
INLET PRESSURE	1239 K PA	(180 PSIA)	1239 K PA	(180 PSIA)
MASS FLOW	7.63 KG/S	(16.8 LB/S)	7.13 KG/S	(15.73 LB/S)
MINIMUM VAPOR QUALITY	93%			
• LOW PRESSURE TURBINE				
POWER	1941 kW	(2603 HP)	1944 kW	(2607 HP)
SPEED	1466 RAD/S	(14,000 RPM)	1466 RAD/S	(14,000 RPM)
NUMBER OF STAGES	4		4	
PRESSURE RATIO	4.4		5.2	
INLET TEMPERATURE	1222 K	(2200 ^{O}R)	1210 K	(2178 ^{O}R)
INLET PRESSURE	425 K PA	(61.7 PSIA)	392 K PA	(56.8 PSIA)
MASS FLOW	7.80 KG/S	(17.2 LB/S)	7.27 KG/S	(16.0 LB/S)
MINIMUM VAPOR QUALITY	89%			

TABLE 3.3.2.1-5

TURBOALTERNATOR TURBINE

200 MW Design

	2 Year Life		10 Year Life	
• **8-stage reaction turbine**				
Materials	T-111 & ASTAR 1511C			
Weight (Turbine Only)	5,870 kg	(12,950 lb)	5,870 kg	(12,950 lb)
• **High pressure turbine**				
Power	31,470 kW	(42,200 hp)	31,240 kW	(41, 890 hp)
Speed	367 rad/s	(3,500 rpm)	367 rad/s	(3,500 rpm)
Number of stages	4		4	
Pressure ratio	2.9		3.2	
Inlet temperature	1450 K	(2610 °R)	1450 K	(2610 °R)
Inlet pressure	1239 kPa	(180 psia)	1239 kPa	(180 psia)
Mass flow	154 kg/s	(339 lb/s)	143 kg/s	(315 lb/s)
Minimum vapor quality	94%		93%	
• **Low pressure turbine**				
Power	39,060 kW	(52,380 hp)	39,190 kW	(52,550 hp)
Speed	367 rad/s	(3,500 rpm)	367 rad/s	(3,500 rpm)
Number of stages	4			
Pressure ratio	4.4		5.2	
Inlet temperature	1222 K	(2200 °R)	1210 K	(2178 °R)
Inlet pressure	425 k Pa	(61.7 psia)	392 k Pa	(56.8 psia)
Mass flow	157 kg/s	(346 lb/s)	146 kg/s	(323 lb/s)
Minimum vapor quality	89%		89%	

TABLE 3.3.2.1-6
ALTERNATOR REQUIREMENTS

	10 MWE	200 MWE
POWER OUTPUT	3.75 MW	70 MW
LIFE	2 AND 10 YEARS	2 AND 10 YEARS
OUTPUT VOLTAGE	7.5 KV OUTPUT	7.5 KV OUTPUT
OUTPUT FREQUENCY	460 HERTZ	180 HERTZ
CONTROL	FIELD VOLTAGE	FIELD VOLTAGE
ROTATING SPEED	14,000 RPM	3,500 RPM
OPERATION	CONTINUOUS	CONTINUOUS

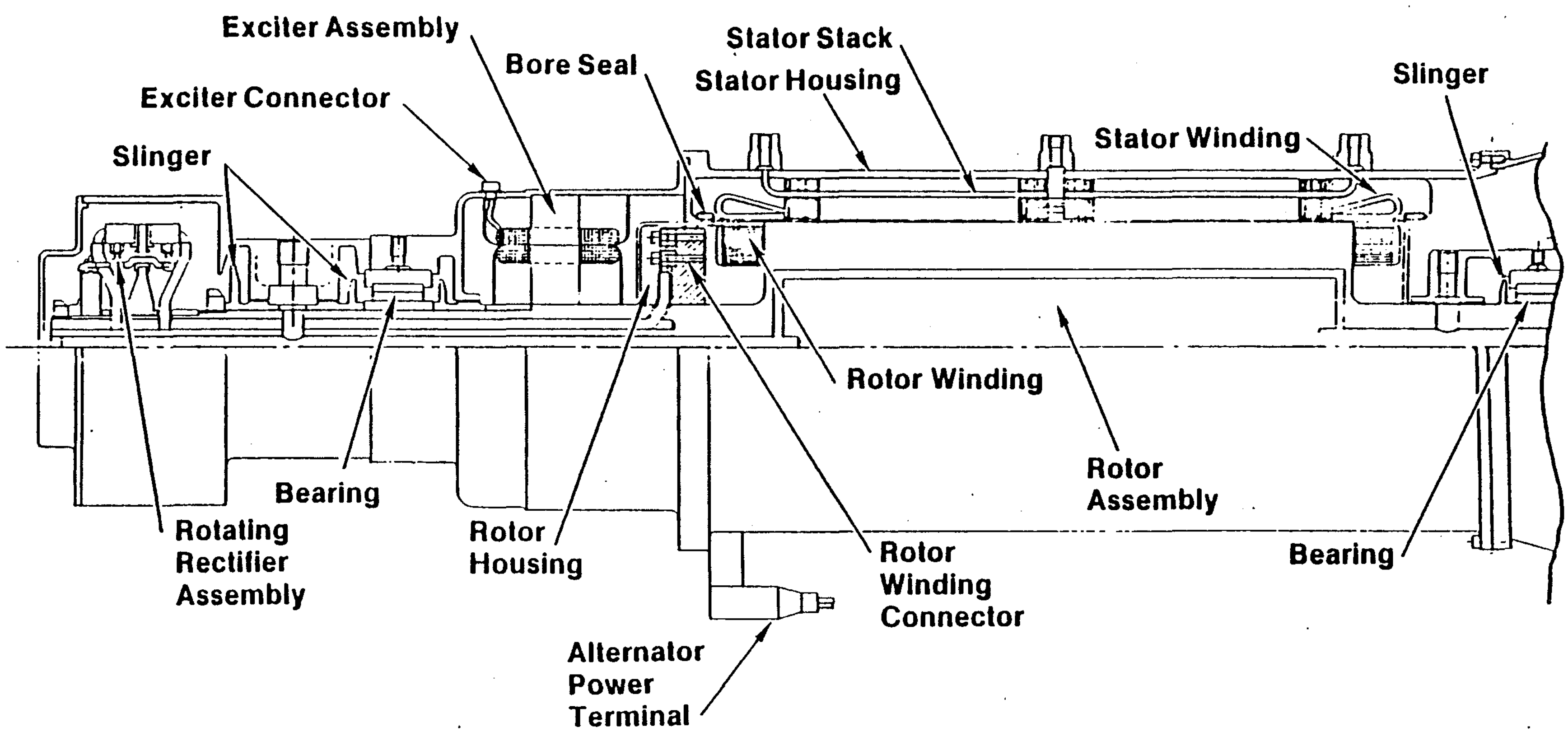
TABLE 3.3.2.1-7
ALTERNATOR CONFIGURATION AND MASS

- CONFIGURATION
  - SALIENT POLE
  - 3 PHASE
  - INTEGRAL EXCITER
  - DIRECT COUPLED TO TURBINE
  - LIQUID COOLED AT 425 - 455 K
- DIMENSIONS AND MASS

	10 MW_E	200 MW_E
DIAMETER	0.50 M	1.2 M
LENGTH WITHOUT EXCITER	1.35 M	3.1 M
LENGTH WITH EXCITER	2.1 M	4.1 M
• MASS/ALTERNATOR	744 KG	8295 KG

FIGURE 3.3.2.1-3

Alternator Physical Layout



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3.3.2.2 Boiler Feed Turbopump (BFTP)

The requirements for the potassium BFTPs for the 10 MWe and 200 MWe systems are listed in Tables 3.3.2.2-1 and 3.3.2.2-2. The pump suction pressure reflects the lower optimum condensing temperature and pressure for the 10-year missions.

A representative cross section for the BFTP is shown in Figure 3.3.2.3-1. The rotating shaft is supported by two radial tilting pad bearings and a bidirectional acting, tilting pad thrust bearing that reacts the net shaft axial loads induced by the turbine.

The boiler feed turbopump employs a one-stage centrifugal impeller with an inducer to produce the required flow and pressure. Material for the pump components is predominantly Nb-1Zr. A one-stage, partial-admission, impulse turbine supplies the required pump power. The turbine stationary components are predominantly T-111 and the rotating components are ASTAR 1511-C (due to higher stress requirements).

The characteristics of the turbine and pump are presented in Tables 3.3.2.2-3 and 3.3.2.2-4 for the 10 MWe and 200 MWe systems. These tables also list the BFTP masses.

TABLE 3.3.2.2-1
BOILER FEED TURBOPUMP
10 MW REQUIREMENTS

	2 YEAR		10 YEAR	
• PUMP				
FLUID	LIQUID POTASSIUM		LIQUID POTASSIUM	
INLET TEMPERATURE	1019 K	(1374^{0}F)	994 K	(1329^{0}F)
INLET PRESSURE	234 K PA	(34 PSIA)	214 K PA	(31.0 PSIA)
DISCHARGE PRESSURE	1314 K PA	(191 PSIA)	1314 K PA	(191 PSIA)
FLOW RATE	8.27 KG/S	(18.22 LB/S)	7.73 KG/S	(17.05 LB/S)
• TURBINE				
FLUID	POTASSIUM VAPOR		POTASSIUM VAPOR	
INLET TEMPERATURE	1450 K	(2150^{0}F)	1450 K	(2150^{0}F)
INLET PRESSURE	1239 K PA	(180 PSIA)	1239 K PA	(180 PSIA)
DISCHARGE PRESSURE	425 K PA	(61.7 PSIA)	392 K PA	(56.8 PSIA)

TABLE 3.3.2.2-2
BOILER FEED TURBOPUMP
200 MW REQUIREMENTS

	2 YEAR		10 YEAR	
• PUMP				
FLUID	LIQUID POTASSIUM		LIQUID POTASSIUM	
INLET TEMPERATURE	1019 K	(1374^{O})	994 K	(1329^{O}F)
INLET PRESSURE	234 K PA	(34 PSIA)	75.8 K PA	(11 PSIA)
DISCHARGE PRESSURE	1386 K PA	(201 PSIA)	1386 K PA	(201 PSIA)
FLOW RATE	163 KG/S	(360 LB/S)	151 KG/S	(17.05 LB/S)
• TURBINE				
FLUID	POTASSIUM VAPOR		POTASSIUM VAPOR	
INLET TEMPERATURE	1450 K	(2150^{O}F)	1450 K	(2150^{O}F)
INLET PRESSURE	1239 K PA	(180 PSIA)	1239 K PA	(180 PSIA)
DISCHARGE PRESSURE	425 K PA	(61.7 PSIA)	392 K PA	(56.8 PSIA)

FIGURE 3.3.2 2-1

Boiler Feed Turbopump Configuration

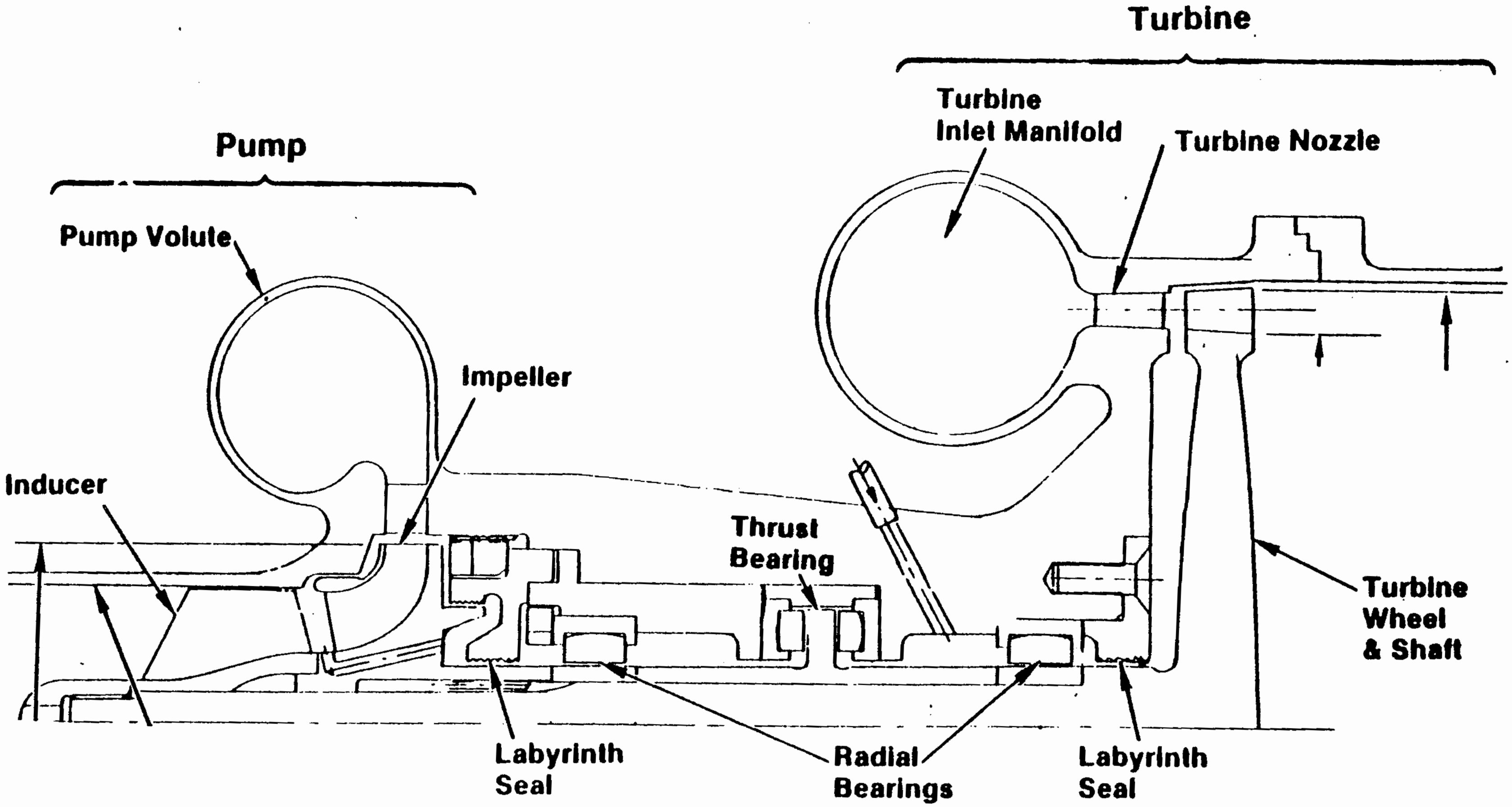


TABLE 3.3.2.2-3

BOILER FEED TURBOPUMP

10 MW DESIGN

	2 Year Life		10 Year Life	
• **Pump**				
Speed	1430 rad/s	(13,670 rpm)	1500 rad/s	(14,350 rpm)
Required Shaft Power	20 k W	(27 hp)	22 k W	(29 hp)
Efficiency	67%		67%	
Pump Type	1 stage centrif. w/inducer			
Material	Nb-1Zr			
• **Turbine**				
Speed	1430 rad/s	(13,670 rpm)	1500 rad/s	(14,350 rpm)
Power	23 k W	(30 hp)	22 k W	(29 hp)
Efficiency	45%		45%	
Turbine type	1 stage impulse, partial adm			
Flow rate	.15 kg/s	(.34 lb/s)	.14 kg/s	(.31 lb/s)
Material	T-111 & ASTAR 1511C			
• **Turbopump weight (each)**	23 kg	(51 lb)	22 kg	(49 lb)

TABLE 3.3.2.2-4

BOILER FEED TURBOPUMP

200 MW Design

	2 Year Life		10 Year Life	
• Pump				
Speed	338 rad/s	(3,223 rpm)	386 rad/s	(3,686 rpm)
Required Shaft Power	427 k W	(572 hp)	450 k W	(603 hp)
Efficiency	67%		67%	
Pump Type	1 stage centrif. w/inducer			
Material	Nb-1Zr			
• Turbine				
Speed	338 rad/s	(3,223 rpm)	1500 rad/s	(3,686 rpm)
Power	427 k W	(572 hp)	450 k W	(603 hp)
Efficiency	45%		45%	
Turbine type	1 stage impulse, partial adm			
Flow rate	3.23 kg/s	(7.13 lb/s)	3.03 kg/s	(6.68 lb/s)
Material	T-111 & ASTAR 1511C			
• Turbopump weight (each)	345 kg	(760 lb)	330 kg	(727 lb)

3.3.2.3 Rotary Fluid Management Device (RFMD)

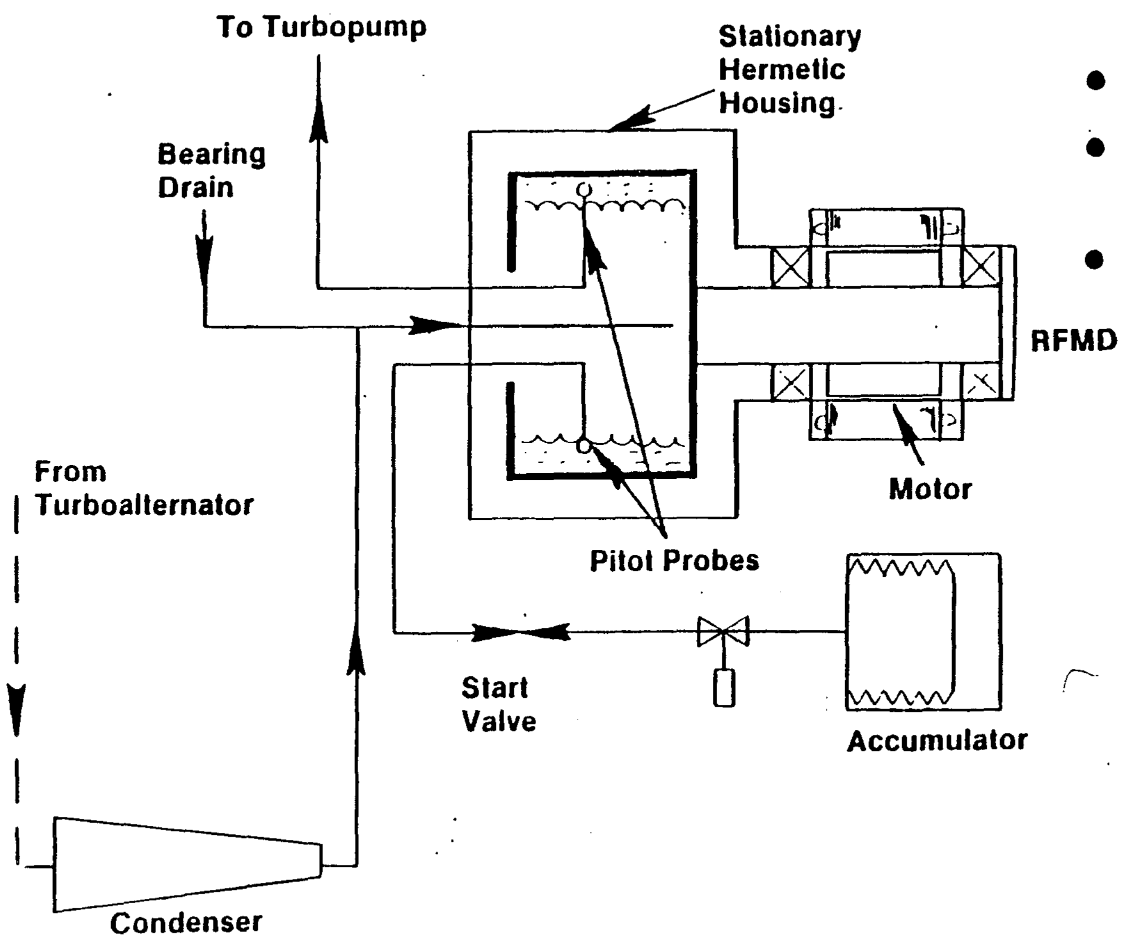
Each power conversion unit in the system is designed with a rotary fluid management device to provide positive, zero-g two-phase fluid management for the potassium Rankine system. The RFMD supplies a small bleed flow to the bearing supply system during PCS start-up. The requirements for the RFMD are listed in Table 3.3.2.3-1, and Figure 3.3.2.3-1 shows the RFMD configuration. Inventory management is provided via an accumulator connected to a pitot pump, which maintains a fixed liquid level in the drum. The cavitation-free capability of the pump minimizes the subcooling required from the condensers. The RFMD pump provides sufficient inlet pressurization to the turbopump to prevent cavitation during PCS steady-state operation and transient conditions. The RFMD design characteristics, and mass are summarized in Table 3.3.2.3-2. The 200 MWe system design employs three RFMDs per PCS unit due to the multiple (3) parallel condenser design used for the main cycle flat-plate radiator.

TABLE 3.3.2.3-1

RFMD DESIGN REQUIREMENTS
PER PCS UNIT

REQUIREMENT	10 MWE SYSTEM	200 MWE SYSTEM
NO. UNITS/PCU	1	3
FLOW RATE (KG/S)	7.73	50.5
NET HEAD (KPA)	138	280

FIGURE 3.3.2.3-1
RFMD
POTASSIUM RANKINE CYCLE APPLICATION



Functions

- Cavitation free pump
- Provides required head to turbopump
- Provides inventory management

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TABLE 3.3.2.3-2

RFMD DESIGN SUMMARY

PARAMETER	10 MWE SYSTEM	200 MWE SYSTEM
MAXIMUM LENGTH (M)	1.0	2.5
MAXIMUM DIAMETER (M)	0.40	1.0
UNIT MASS (KG)	243	870
INPUT POWER (KWE)	11.2	130
COOLING REQUIREMENT (KWT)	5.4	62
SPEED (RPM)	1,550	3,600
TOTAL RFMD MASS PER MISSION, KG		
TWO-YEAR	972	10,440
TEN-YEAR	1,215	13,050

3.3.2.4 PCS Piping and Auxiliaries

The power conversion system (PCS) consists of four (and five) parallel potassium Rankine power conversion loops. Three of the PCS loops are required to provide full power output from the system. The fourth PCS loop is provided in a nonoperating condition in the event of a PCS component failure for the two year mission. A second standby PCS unit is included for the 10 year mission. The requirements for the PCS loops are listed in Table 3.3.2.4-1, and a Mass breakdown is given in Table 3.3.2.4-2.

TABLE 3.3.2.4-1

PCS POTASSIUM LOOP PIPING REQUIREMENTS

REQUIREMENTS PER LOOP	10 MWE SYSTEM	200 MWE SYSTEM
THERMAL INPUT (MWT)	16	328
FLOW RATE (KG/S)	7.3	146
LINE SIZES (M)		
TURBINE INLET	.117	.52
BOILER INLET	.063	.28
REHEATER	.228	.76

TABLE 3.3.2.4-2
PCS POTASSIUM LOOP PIPING AND AUXILIARIES MASS SUMMARY

COMPONENTS	MASS (KG)/PER PCS UNIT	
	10 MWE SYSTEM	200 MWE SYSTEM
ELECTRICAL HEATERS	25	110
AUXILIARY COOLING RECUPERATOR	25	500
AUXILIARY POTASSIUM COOLER	20	400
POTASSIUM INVENTORY	405	1,800
ACCUMULATORS	195	870
PIPING AND VALVES	270	1,210
SUBTOTAL	940	4,890
TOTAL POWER SYSTEM MASS, KG		
TWO-YEAR MISSION	3,760	19,560
TEN-YEAR MISSION	4,700	24,450

3.3.3 Heat Rejection Subsystem

The heat rejection subsystem is made up of the main cycle radiator as well as radiators for auxiliary cooling loops, power conditioning rectifier cooling and alternator cooling. The requirements for these radiators are listed in Tables 3.3.3-1 and 3.3.3-2. The operating requirements were obtained from the overall weight optimization described in Section 3.1.1. The optimum condensing temperature for the ten-year life power systems are seen to be lower than the two-year life systems because the heavier reactors associated with the longer fuel burnup result in a weight optimum at a higher efficiency (lower condenser temperature).

The main cycle radiator is made up of heat pipes attached to the main condenser. The condenser is a shear-controlled design with tapered channels to maintain high vapor velocity along the condenser length, sweeping the condensate to the outlet. Figure 3.3.3-1 shows how the four or five condensers, depending on the redundancy required for 2 or 10 year missions, are integrated with the heat rejection radiators. Each condenser module is made up of dual tapered rectangular channels attached to the evaporators of the heat pipe panels. The condensation process maintains the radiator panels at near uniform temperature.

The radiator panels are composed of finned heat pipe assemblies. The radiator fin and armor are fabricated from carbon-carbon composite material. For the potassium working fluid the heat pipe will employ a metal coating. From operational considerations, the radiator heat pipe length has been limited to 15 meters. This requires the use of three condenser/heat pipe radiator panels in parallel to minimize overall system length for the 200 MWe system as was seen in Figure 3.2-2.

There are three auxiliary radiators required to support the power generation system. The auxiliary loop radiator is designed to reject the heat collected by a lithium loop cooling used to cool some of the primary loop and PCS components. The alternator cooling radiator functions similarly with a NaK loop used to cool the alternator. Both radiators use finned carbon-carbon composite heat pipe panels for direct contact with the outer shell of a duct to provide for the actual heat rejection. The rectifier or power conditioning radiator provides a cold plate for mounting of the electronics equipment. Heat is removed from the cold plate by way of large diameter transport heat pipes which subsequently are cooled by the radiator panels. Figure 3.3.3-2 shows the basic configuration of these radiators.

The mass and area requirements for the main cycle and auxiliary radiators are listed in Tables 3.3.3-3 and 3.3.3-4. The major differences in the radiator masses for 2 and 10-year missions are the additional meteoroid armor and the added redundant PCS (condenser or radiator heat exchanger) for the 10-year radiators.

TABLE 3.3.3-1

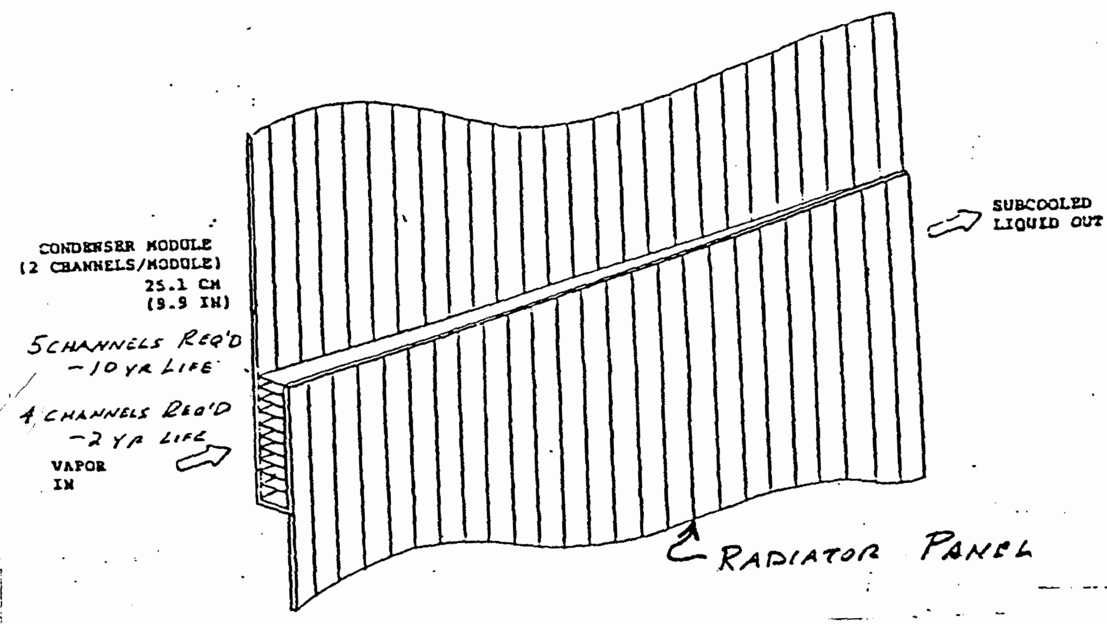
CONDENSER/MAIN CYCLE RADIATOR REQUIREMENTS

	10 MW_E	200 MW_E
DUTY (2 YEAR/10 YEAR) (MW_T)	40.5/37.8	814.8/759.9
SERVICE LIFE (YEARS)	2, 10	2, 10
AVERAGE SURFACE TEMP (K)	994 - 10 YEARS 1019 - 2 YEARS	994 - 10 YEARS 1019 - 2 YEARS
ENVIRONMENT	EARTH - MARS	EARTH - MARS
AVERAGE SINK TEMP (K)	145	145
REDUNDANCY (OPERATING UNITS/STANDBY)	3/2 - 10 YEARS 3/1 - 2 YEARS	3/2 - 10 YEARS 3/1 - 2 YEARS

FIGURE 3.3.3-1

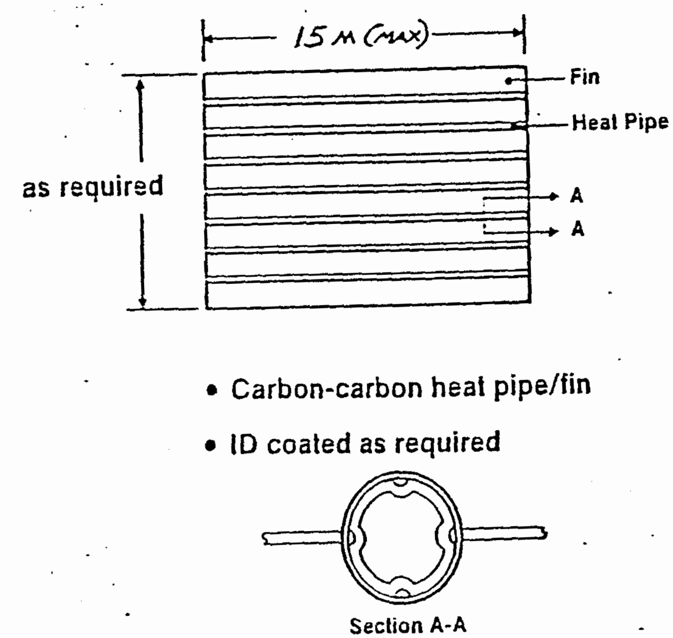
CONDENSER/MAIN RADIATOR CONFIGURATION

- **CONDENSER CONFIGURATION**



- **PANEL CONFIGURATION**

• Single panel design serves all applications



• Carbon-carbon heat pipe/fin

• ID coated as required

FIGURE 3.3.3-2
AUXILIARY RADIATOR CONFIGURATIONS

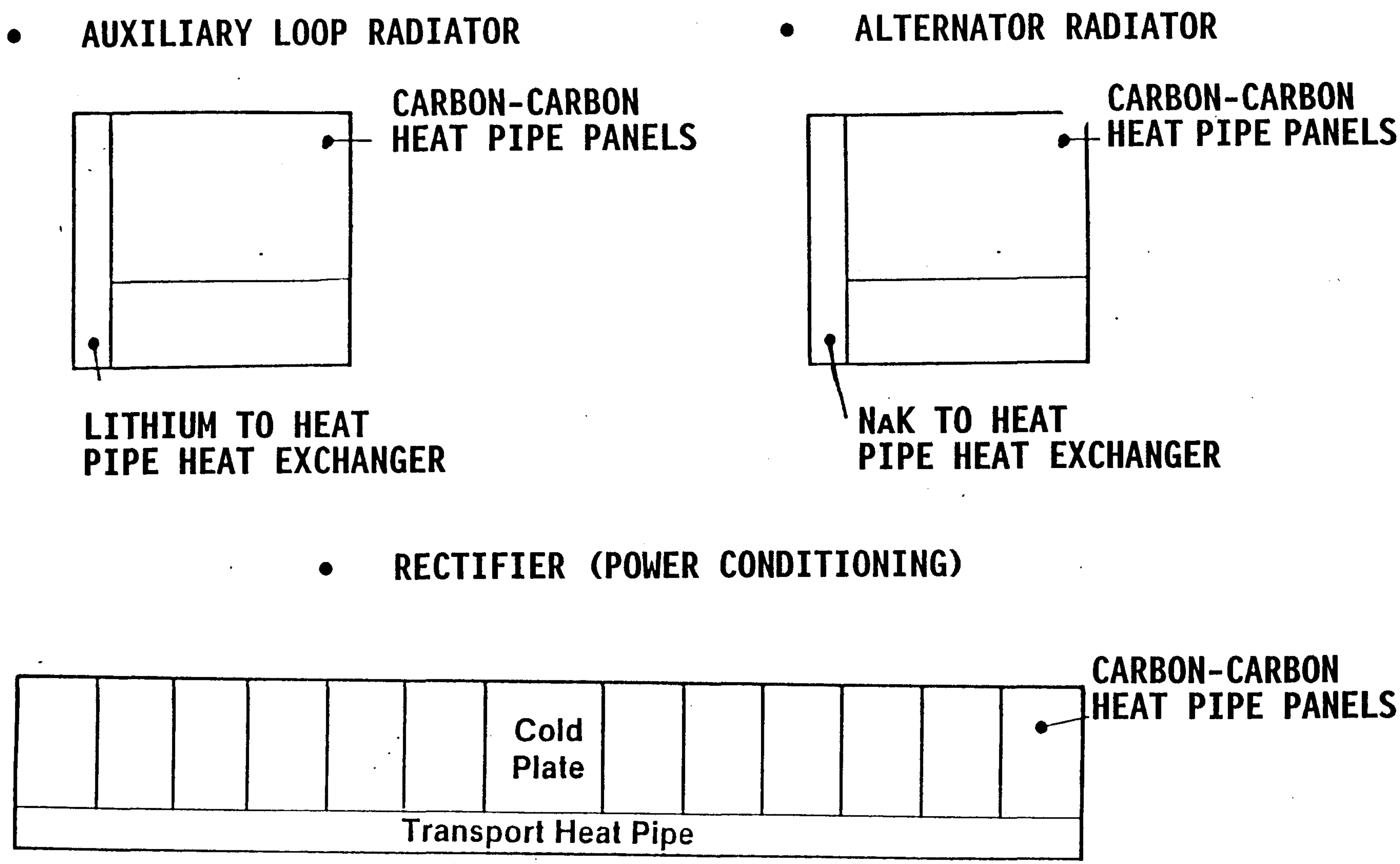


TABLE 3.3.3-2
AUXILIARY RADIATOR REQUIREMENTS

	10 MWE	200 MWE
DUTY (2 YEAR/10 YEAR) (MWT)		
- RECTIFIER COOLING	0.103/0.103	2.10/2.10
- ALTERNATOR COOLING	0.430/0.430	5.30/5.30
- AUXILIARY (PUMPS, BEARINGS, ETC.)	0.536/0.536	6.20/6.20
SERVICE LIFE (YEARS)	2/10	2/10
AVERAGE SURFACE TEMP (K)		
- RECTIFIER COOLING	398	398
- ALTERNATOR COOLING	436	436
- AUXILIARY LOOPS	650	650
ENVIRONMENT	EARTH/MARS	EARTH/MARS
AVERAGE SINK TEMP (K)	145	145
REDUNDANCY (OPERATING UNITS/STANDBY)	3/2 - 10 YRS 3/1 - 2 YRS	3/2 - 10 YRS 3/1 - 2 YRS

TABLE 3.3.3-3

CONDENSER/MAIN RADIATOR AREA AND MASS

	10MWE	10MWE	200MWE	200MWE
SERVICE LIFE (YEARS)	2	10	2	10
RADIATOR PLANFORM* AREA (M^2)	576	596	11,595	11,998
CONDENSER MASS (KG)	635	794	10,124	12,655
RADIATING SURFACE MASS (KG)	1563	2037	31,463	41,005
TOTAL MAIN CYCLE HEAT REJECTION SUBSYSTEM MASS (KG)	2198	2831	43,058	53,003

* ONE-HALF THE EFFECTIVE RADIATOR SURFACE AREA

TABLE 3.3.3-4

AUXILIARY RADIATORS AREA AND MASS

SIZE AND MASS ELEMENT	10MWE	10MWE	200MWE	200MWE
SERVICE LIFE (YEARS)	2	10	2	10
RADIATOR PLANFORM* AREA (M^2)				
- RECTIFIER	78	78	1,590	1,590
- ALTERNATOR	192	192	2,367	2,367
- AUXILIARY	53	53	613	613
RADIATOR HEAT EXCHANGERS MASS (KG)	635	794	10,124	12,655
RADIATOR SURFACE MASS (KG)				
- RECTIFIER	152	191	3,082	3,881
- ALTERNATOR	372	470	4,598	5,791
- AUXILIARY	118	149	1,363	1,716
TOTAL AUXILIARY HEAT REJECTION SUBSYSTEM MASS (KG)	1,277	1,604	19,167	24,043

*ONE-HALF THE EFFECTIVE RADIATOR SURFACE AREA

Mass estimates are based on the radiator area required, the radiator configuration, i.e., conical or flat plate, and the mass estimates developed for the NASA sponsored, SP-100 Advanced Radiator Program. The SP-100 Advanced Radiator Program reported[3] a radiator specific mass, exclusive of manifolds, piping, etc. of 4.73 Kg/(Sq.-Meter) for a high temperature space radiator operating at conditions similar to the main radiator in this study. The SP-100 advanced radiator operates at a high fin efficiency due to the fact that the minimum mass of a conical radiator coincides with a high fin efficiency. The minimum mass flat plate radiators selected for these applications usually optimize at slightly lower fin efficiency values, and consequently have lower specific masses, since the lightweight fin now occupies a greater percentage of the surface. The temperature of the radiator also influences the optimum mass operating point. Lower temperature radiators usually optimize at still lower fin efficiencies. The optimized radiator parameters that resulted from these designs for electrical propulsion are compared to the SP-100 advanced radiator in Table 3.3.3-5, below.

TABLE 3.3.3-5
Ultra-High Power Space Nuclear Power
Radiator Design Parameter Comparison
(10-Year Mission)

Radiator	Avg. Temp. K	Fin Spacing (Cm.)	Fin Eff.	Specific Mass (Kg/sq-Meter)
Advanced SP-100/TE	800	2.28	0.9	4.73
Main Cycle Heat Rejection	1000	4.83	0.8	3.42
Rectifier Cooling	398	7.62	0.7	2.44
Alternator Cooling	436	7.62	0.7	2.44
Auxiliary Cooling Loop	650	6.35	0.75	2.78

Note that the specific mass values given in Table 3.3.3-5 do not include the manifolds (condensers) and refer to the specific mass of a panel with a planform area. For a flat plate radiator, the effective radiating area is twice the planform area. A surface emissivity of 0.8 was employed throughout to determine area requirements. Each radiator is oversized by 11.0% to provide for redundant heat pipes and working area. The radiators for the two-year mission are approximately 79% of the mass of the ten-year radiators due to reduced heat pipe armoring requirements.

[3] NASA Contractor Report 182174, "Advanced Radiator Concepts for SP-100 Space Power Systems - Phase II Final Report", Rockwell International Rocketdyne Division, Contract NAS3-25209, October 1988

The balance of the heat rejection system masses were estimated from results obtained for previous high power liquid metal Rankine cycle system designs and from previous SP-100 studies conducted at Rocketdyne over the last several years.

3.3.4 Power Conditioning Subsystem

The power conditioning system is based on a regulation and rectification stage connected to the output of the alternator. The power conditioning requirements are listed in Table 3.3.4-1. The alternators provide sufficient voltage that the required direct current voltage can be achieved without step up transformers. Power conditioning trade studies have shown that the increase in efficiency and reliability achieved by a lower temperature system more than compensates for the mass of the required thermal management system. Higher temperature power conditioning systems are more massive due to the extreme derating required for the components and are lower in efficiency resulting in heavier energy source component masses.

To provide a high power, reliable power conditioning system, Rocketdyne has provided a modular system in which a number of identical modules are connected in parallel to achieve the total output power level. This modularity provides improved reliability in that extra modules can be provided without a significant increase in weight and robustness such that a failure in a given module can be accommodated by a nominal increase in power level on the other modules.

This system with four (five) alternators will have a number of regulator and rectifier stages operating in parallel to supply a common direct current output bus. Each alternator will supply a group of these modules and the alternators will not be required to operate in parallel. Thus, synchronous operation of the alternators is not required. Figure 3.3.4-1 shows the electrical schematic.

The regulators can be SCRs in bridge arrangements operating in phase delay mode to control the alternating current voltage or saturable reactors with auxiliary windings connected to parasitic load resistors. The reactors shown in Figure 3.3.4-1, present a more reliable alternative and are less subject to voltage limitations. When saturated by the control current, the reactors present relatively low impedance to the primary current flow. This scheme provides the benefits of voltage regulation and a parasitic load to dissipate system energy during a fault interruption event. The reactors have a higher radiation resistance potential than the SCRs and the mass penalty of magnetic devices is minimized by designing the alternators for the highest practical output frequency.

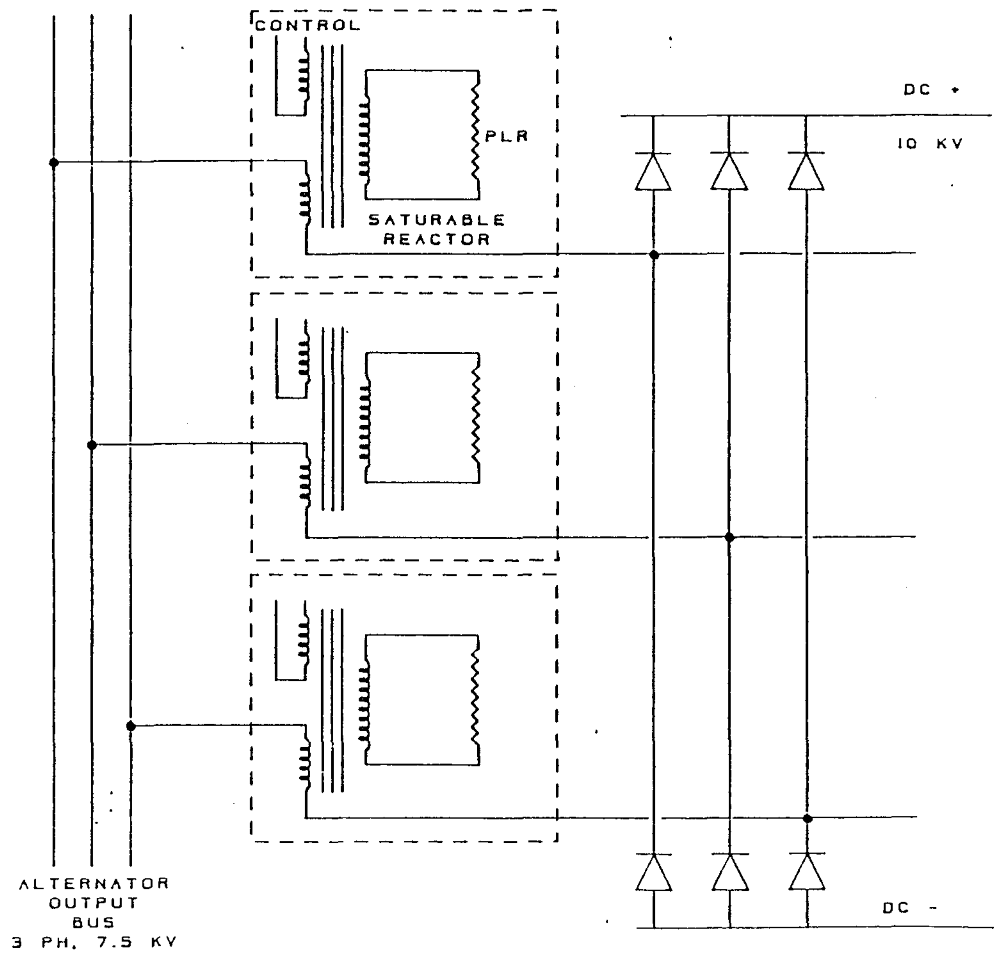
The rectification stages will consist of FETs operating in a synchronous rectification mode. This type of operation provides a high efficiency, especially in low voltage applications, but is dependent upon the development of devices to operate at the required voltage levels. An alternative would be stacked diodes in a ceramic insulating structure to provide direct rectification. At the required output voltage, the forward drop of the diode stack will be a small fraction of the total voltage and the rectification efficiency will be high. An estimated drop of 50 volts in the rectifier results in an efficiency of 99.5%.

Primary voltage control is accomplished by control of the alternator fields. Fine control of the voltage will be provided by the saturable

TABLE 3.3.4-1
POWER CONDITIONING REQUIREMENTS

POWER LEVEL	10 MW AND 200 MW
OUTPUT VOLTAGE	10 KV DIRECT CURRENT
LIFE	2 AND 10 YEARS
OPERATION	CONTINUOUS

FIGURE 3.3.4-1
HIGH VOLTAGE POWER CONDITIONING CONCEPTUAL SCHEMATIC



reactors and parasitic loads. The degree of voltage variation will be the subject of a trade study to determine the minimum weight regulation system consistent with user voltage tolerance requirements. The system using alternators and saturable reactors is inherently stiff, that is, the source impedance is low and variation in load current will result in relatively low variations in output voltage. The regulation system will be designed to provide the required degree of voltage regulation with system weight generally being directly proportional to the level of control required. The alternator is designed to provide output voltage in the range required for conversion to the required DC voltage without step up transformation.

The voltage control will consist of a two loop control system with a slow, wide range loop (the generator field) for control of large load variations and a faster, narrow range loop (the saturable reactors) for fine control. The characteristics of each control loop will be considered in the development of the voltage control algorithms and the system will be designed to preclude instabilities due to the interaction of the two control loops.

The power conditioning system configuration and mass are listed in Table 3.3.4-2. The design is modular and may be arranged to fit the space available and to minimize shielding requirements. Therefore, only total volume estimates are given in the charts.

TABLE 3.3.4-2
POWER CONDITIONING, CONFIGURATION AND MASS

- REGULATION OF ALTERNATOR OUTPUT SYNCHRONOUS RECTIFICATION LIQUID COOLED AT 400 K

VOLUME, M^3

10 MW - 1 TOTAL

200 MW - 20 TOTAL

MASS, KG

10 MW - 468 KG

200 MW - 9360 KG

4.0 Technology and R&D Impacts

This section addresses the research issues requiring resolution to permit a confident start on full scale development, an assessment of the program technical risks, the overall program schedules for development of the 10 MWe and 200 MWe systems, the estimated costs of developing the two systems, and the impacts of incorporating several very advanced technologies in the system.

At the completion of the development programs described here, the systems will have been brought to a NASA technical readiness level of 8, "Flight Qualified System."

4.1 Research Issues

Table 4.1-1 lists the research issues for the nuclear potassium Rankine cycle system. The basis for this list is the technical risk assessment delineated in Section 4.2. The Ultra High Power Space Nuclear System is largely based on proven technology except for the reactor fuel, which is expected to require substantial in-reactor testing to establish high burnup capability. The remainder of the research issues are significant and require resolution, but are not as critical as that mentioned above.

The research issues listed are the same for both the 10MWe and the 200MWe systems, since the size of the system does not affect the fundamental data needed for its design. Of course, the 200MWe system will require a more extensive development and qualification program than the 10MWe system, after the research issues have been satisfactorily resolved.

TABLE 4.1-1 RESEARCH ISSUES

ISSUE	REQUIRED DATA
CERMET FUEL PERFORMANCE	FUEL CRACKING UNDER LONG TERM (HIGH BURNUP) STEADY STATE AND THERMAL CYCLING CONDITIONS
CARBON-CARBON COMPOSITE COATING, MANUFACTURING, AND JOINING	DEVELOPMENT OF PROTECTIVE COATINGS FOR POTASSIUM AND SODIUM TUBULAR JOINT PROPERTIES
LONG TERM RELIABILITY OF HIGH TEMPERATURE ELECTROMAGNETIC PUMP MATERIALS	PHYSICAL PROPERTIES OF CONDUCTORS, INSULATORS, BRAZE ALLOYS, AND MAGNETIC MATERIALS AT HIGH TEMPERATURES
TEMPERATURE SENSORS FOR 1550K SERVICE	FABRICATION TECHNIQUES, PERFORMANCE, RELIABILITY AND LIFE OF ADVANCED TEMPERATURE SENSORS

4.2 Technical Risk Assessment

The research issues summarized in the previous section result from an examination, component by component, of the current state-of-the-art, and the data needed, if any, to permit a confident start on a half-scale development program. This technical risk assessment is shown, largely in tabular form, in this section. It is organized by the following major subsystems:

- Reactor
- Primary Loop
- Potassium Loop
- Turboalternator
- Heat Rejection System
- Auxiliary Systems
- Control and Instrumentation
- Power Conditioning.

For each major component of each of the listed subsystems, there is a brief narrative summary of the current state-of-the-art, a listing of the NASA Technology Readiness Level, and a brief summary of the data needed to bring the component to a point of readiness for full-scale development. The NASA Technology Readiness Level scale is shown in Table 4.2-1.

None of the individual components exceeds a technology radiness level of 4 and most of them are 3 or less. This does not in itself require that "research" be accomplished to permit start of a development program on the component. The need for research is identified only where it is judged that there is a significant lack of technical data available to support the component design.

Table 4.2-1. NASA Technology Readiness Levels

LEVEL 1	BASIC PRINCIPLES OBSERVED AND REPORTED
LEVEL 2	CONCEPTUAL DESIGN FORMULATED
LEVEL 3	CONCEPTUAL DESIGN TESTED ANALYTICALLY OR EXPERIMENTALLY
LEVEL 4	CRITICAL FUNCTION/CHARACTERISTIC DEMONSTRATION
LEVEL 5	COMPONENT/BRASSBOARD TESTED IN RELEVANT ENVIRONMENT
LEVEL 6	PROTOTYPE/ENGINEERING MODEL TESTED IN RELEVANT ENVIRONMENT
LEVEL 7	ENGINEERING MODEL TESTED IN SPACE
LEVEL 8	"FLIGHT-QUALIFIED" SYSTEM
LEVEL 9	"FLIGHT-PROVEN" SYSTEM

TECHNOLOGY DEVELOPMENT

ADVANCED DEVELOPMENT

FLIGHT SYSTEMS

4.2.1 Reactor Technology Assessment

Table 4.2-2 summarizes the state of the art, technology readiness level, and needed research for the reactor components. Because of their potential for high burnup and capability to withstand rapid power transients, cermet fuels have received development attention by the various national laboratories. Feasibility of coating 100-μm UN fuel particles with W-25Re and densifying the cermet has been successfully demonstrated using TiN as a surrogate for UN, and UN/W-25Re compatibility tests have been performed at 1700 and 1900 K. Specimens of UN-W fuel were fabricated and irradiated in the Battelle Research reactor in the mid-1960s. All testing performed to date indicates that UN/W-25Re has high-temperature strength, high thermal conductivity, good thermal shock resistance, high density, and high burnup capability. However, very little data exists for the specific UN/W-25Re cermet fuel planned. Some fabrication development has been performed, but currently there are no irradiation data available. For these reasons, a research program to establish fabrication techniques and to assess the irradiation behavior of the cermet fuel at up to high burnups (capability of fuel form is estimated to be on the order of 25%) is needed as a precursor to full-scale reactor development.

Table 4.2-2. Reactor Technology Assessment

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Core and Fuel	Neutronics and thermal hydraulics calculational methods are well established (No boiling in core.) Cermet fuel fabrication feasibility has been established but not optimized. Applicable irradiation data are minimal	1	Cermet fuel fabrication process development. Cermet fuel irradiation behavior at temperature to 25% burnup.
Vessel and internals	Coolant flow geometry is conventional. Vessel is standard cylindrical shape Core support by grid plates is standard practice. Thermal hydraulic calculations are standard practice. ASTAR 811C material is available in pilot plant quantities, and has a substantial high-temperature data base.	3	None required.
Fixed Reflector	Neutronic calculations are standard practice. Active cooling is provided. Materials are available.	3	None required.
Control Rod Assemblies	Neutronic calculations are standard practice. Actuator design is conventional. B_4C and T-111 materials are available. Safety rods move within dry wells. Bellows seals or "canned" drives will be required to contain liquid metal for the active control rods.	2	None Required

4.2.2 Primary Loop Technology Assessment

Table 4.2-3 summarizes the state of the art, technology readiness level, and needed research for the primary loop components. Since the primary loop EM pumps operate at higher temperatures than current liquid metal EM pumps, there is a lack of data on the long-term properties of the structural, brazing, electrical, magnetic and insulating materials used to fabricate the pump. Testing will be required to obtain these data.

Table 4.2-3. Primary Loop Technology Assessment
(Sheet 1 of 2)

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Jet Pump	Water jet pumps are in common use. Potassium jet pump was operated for 18,000 h on MPRE program.	4	None required.
Decay heat removal pump	Thermoelectrically driven dc conduction pumps were developed on SNAP-10A program. Total accumulated operating time was 200,000 h. Thermoelectric materials previously used (SiGe) good to 1300 K, which is adequate with cooling on the pump.	4	None required.
Expansion compensator	Fifty expansion compensators tested for over 10,000 h on SNAP-10A program. ASTAR 811C material is commercially available in pilot plant quantities. Bellows of this size are in common use.	4	None required.
Piping	ASTAR 811C material for the high temperature piping is available in pilot plant quantities. 7500 h test loop with ASTAR 811C samples showed no corrosion or carbon depletion.	4	None required.
Primary loop pump	ASTAR 811C for the pump throat is available in pilot plant quantities. A helical induction pump successfully pumped 1534 K lithium for 10,000 h. Long-term behavior of structural, brazing, electrical, magnetic, and insulating materials require characterization.	2	Long-term property data on structural, brazing, electrical, magnet, and insulating materials

Table 4.2-3. Primary Loop Technology Assessment (Sheet 2 of 2)

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Oxygen control	Need for getters will eventually be developed as part of materials base technology.	2	None required.
Gas removal	SP-100 gas removal system will be employed.	3	None required.
Trace heating	Electrical resistance heaters commonly used on liquid metal piping. Materials must be selected for the high temperature.	4	None required.
Insulation	Multifoil insulation used on Kilowatt Isotope Power System (KIPS), Brayton Isotope Power System (BIPS), and other space programs.	4	None required.
Armor	C-C composite material can be fabricated in required shapes.	2	None required.

4.2.3 Potassium Loop Technology Assessment

Table 4.2-4 summarizes the state of the art technology readiness level, and needed research.

Considerable research and development has been accomplished to establish the practicality of boiling potassium components. In the Medium-Power reactor Experiment, ORNL demonstrated successful operation of various components and subsystems, at a turbine inlet temperature of 1150 K. Data were obtained on the heat transfer and burnout limitations for boiling potassium, and good boiling-flow stability and flow distribution were demonstrated in electrically heated core mock-ups. Nucleation rings were developed to provide a satisfactory method of initiating and maintaining smooth nucleate boiling of potassium. A tapered tube direct-condensing radiator was developed and shown to provide uniform flow distribution with good flow stability. Performance of typical jet pumps in the cavitating regime was established and the pump characteristics for zero-g operation of a Rankine cycle were demonstrated.

In the SNAP-50 boiling potassium program, boiling potassium components, including a boiler, were tested for a total of approximately 16,000 h.

An issue that has received a great deal of attention in two-phase systems is that of management of the condensing fluid. Techniques for accomplishing this have been developed in support of the Space Station Freedom Electric Power System and the Dynamic Isotope Power System. both these applications considered the use of an organic-Rankine cycle for power conversion. Sundstrand Corporation developed and tested a rotary fluid management device that generates an artificial gravity for fluid-vapor separation. This device is used in conjunction with a shear flow condenser to predictably separate vapor and fluid. Operation has been convincingly demonstrated in short duration KC-135 zero-g tests.

Table 4.2-4. Potassium Loop Technology Assessment
(Sheet 1 of 2)

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Boiler/reheater	ASTAR 811C material is available in pilot plant quantities. See primary loop piping for past ASTAR 811C testing. Feasibility of lithium-heated boiler for vaporizing potassium demonstrated in ORNL and NASA experiments, which operated at potassium exit temperatures of 1450 K. Droplet carryover in superheated vapor has been noted.	4	None required.
Boiler feed turbopump	Potassium turbopump has been tested at 1100 to 1150 K for 2,500 h. ASTAR 811C material is available in pilot plant quantities. Nb-1Zr is commercially available.	4	None required.
Rotary fluid management device (RFMD)	Small-scale RFMDs tested on Space Station Freedom program, and boost surveillance and tracking satellite (BSTS) program using organic working fluid. KC-135 zero-g tests have been successful. Nb-1Zr is commercially available. Experience with potassium working fluid in an RFMD will be obtained during component development program.	4	None required.
Stop valve	Valve is conventional design. Nb-1Zr material is commercially available. Reliability at operating temperature must be established during development program.	3	None required.
Start valve	Same as stop valve.	3	None required.

Potassium Loop Technology Assessment
(Sheet 2 of 2)

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Control valve	Same as stop valve, except valve is ASTAR 811C, which is commercially available in pilot plant quantities.	3	None required.
Accumulator	Similar, but much smaller accumulators used on SNAP program. Nb-1Zr material commercially available. Bellows commonly made in required sizes.	4	None required.
Bearing supply cooler	Conventional heat exchanger design. Nb-1Zr material commercially available.	3	None required.
Bearing supply recuperator	Same as bearing supply cooler.	3	None required.
Piping	ASTAR 811C material has been tested (see primary piping) and is available in pilot plant quantities. Nb-1Zr material is commercially available.	4	None required.
Trace heating	Electrical resistance heaters used on liquid metal piping. Materials must be selected for high temperature.	4	None required.
Insulation	Multifoil insulation used on Kilowatt Isotope Power System (KIPS), and other space programs.	4	None required.
Armor	C-C composite material can be fabricated in required shapes.	2	None required.

4.2.4 Turboalternator Technology Assessment

Table 4.2-5 summarizes the state of the art, technology readiness level, and needed research for the turboalternator components.

Extensive potassium turbine experience exists. Past potassium turbines have been designed for temperatures as high as 1450 K. Turbine materials have been demonstrated in T-111 potassium loops; however, dynamic testing has been performed only at temperatures in the 1100 K range to study potential blade erosion in the wet region of the turbine. ASTAR 1511-C material properties have been measured and are adequate for its use in the turbine blades and rotor.

Both two-stage and three-stage potassium reaction turbines have been tested, specifially to determine the extent of turbine erosion in the final stages. The two-stage turbine operated for 5,100 h with negligible erosion, and the three-stage turbine for 5,000 h with a similar result.

Tilting pad bearings, planned for the turboalternator, are extensively used. Potassium lubricated bearings have been successfully tested in bearing test rigs for a total of approximately 9,000 h.

Table 4.2-5. Turboalternator Technology Assessment

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Turbine	ASTAR 1511C material for the disc and blades was produced in the early 1970s in small quantities. Technology for forging fabrication must be reestablished. ASTAR 811C material is commercially available in pilot plant quantities. Potassium turbine (final stages) tests have been successfully performed, showing acceptable erosion of blades. Recent water tests show that removal of moisture collection on final stator may be required. Tests have demonstrated methods to remove moisture. Erosion not a problem in tests.	4	None required.
Turbine and alternator bearings and data seals	Tilting pad bearings are in common use and have a large base. Short-term tests of potassium bearings in the proper temperature range have been successful.	4	None required.
Alternator	Lower temperature wound-field synchronous type design has a long application history. Materials of construction are readily available and well characterized. New design employs stainless steel bore seal.	3	None required.

4.2.5 Heat Rejection System Technology Assessment

Table 4.2-6 summarizes the state of the art, technology readiness level, and needed research for the main condenser and the five radiators that constitute the heat rejection system.

Adequate data are available for the shear flow condenser hydraulic design. The state of the art of the five radiators is similar. The analytical tools for the heat pipe designs are available and have been proven in practice. All of the heat pipes are made of carbon-carbon composite material with a protective coating. It may be possible to select a single protective coating suitable for all working fluids (potassium, water, and ethanol), but in any event, testing will be necessary to select an appropriate coating and to establish techniques for its application.

Table 4.2-6. Heat Rejection System Technology Assessment

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Condenser	Design methods for shear flow condenser have been validated on Organic Rankine Cycle program. KC-135 tests have verified performance in zero-g. Operation with potassium will be verified in development program. Limited data are available on properties of C-C composite materials. Fabrication of various shapes has been demonstrated. Nb-1Zr material for the liner is commercially available.	2	Fabrication of C-C composite shapes. Insertion of Nb-1Zr liner and joining of lined C-C composite to Nb-1Zr piping.
Main Radiator	Heat pipe operation in zero-g has been demonstrated generically. See comments for condenser regarding C-C composite material.	2	Fabrication of niobium or nickel coated CCC heat pipes.
Alternator Cooling Radiator	Same as main radiator, except that C-C composite is carbon sealed rather than nickel coated -- must be compatible with water.	2	Fabrication of C-C composite shapes and sealing with dense carbon. Compatability with water.
Auxiliary System Radiator	Same as main radiator.	2	Same as main cooling radiator.
Rectifer Cooling Radiator	Same as alternator cooling radiator, except that C-C composite seal must be compatible with ethanol.	2	Same as alternator cooling radiator. Compatibility with ethanol.

4.2.6 Auxiliary Systems Technology Assessment

Table 4.2-7 summarizes the state of the art, technology readiness level, and needed research for the components of the auxiliary systems.

Table 4.2-7. Auxiliary Systems Technology Assessment

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Thermoelectric-magnetic pump	Smaller but similar pump used on SNAP-10A. Nb-1Zr material commercially available.	3	None required.
Expansion compensator	Similar design used on SNAP-10A expansion compensator.	3	None required.
Piping	Nb-1Zr material is commercially available.	3	None required.
Trace heating	Electrical resistance heaters commonly used on liquid metal piping.	4	None required.
Insulation	Multifoil insulation used in KIPS, BIPS, and other space programs	4	None required.

4.2.7 Control and Instrumentation Technology Assessment

Table 4.2-8 summarizes the state of the art, technology readiness level, and needed research for the various classes of control and instrumentation.

Some moderate extension of the current state of the art with respect to temperature capability of the electronics will be necessary, however, this is not regarded as a technology issue. Improvements in this characteristic are expected as part of the normal development of these devices.

Table 4.2-8 Control and Instrumentation Technology Assessment (Sheet 1 of 2)

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Electronics (computers, signal, conditioning equipment, etc.)	Commercially available for 343 to 398 K.	3	None required.
Flow sensors	Electromagnetic flow meters are in wide use. Will require high-temperature windings.	3	None required.
Temperature sensors	High-temperature thermcouples (e.g., W-Re) are available for temperatures up to 1350 K. For higher temperatures (e.g., 1550 K), there are currently no tested devices.	1	Design and testing of temperature sensors capable of operation at 1550K.
Pressure sensors	Bellows or diaphragm seal assemblies with liquid metal transmission are in wide use.	4	None required.
Speed sensors	Required for turbopump only. Will require high-temperature windings.	3	None required.
Flux sensors	High-temperature flux sensors will be available for 873 K in the short term. Will use in cooler location.	4	None required.
Control rod and safety rod position indicators (step counting devices)	Fixed position switches to be used will utilize technology developed on SNAP 8 and 10.	4	None required.

4.2-8. Control and Instrumentation Assessment (Sheet 2 of 2)

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Valve actuators	Solenoid or motor-driven actuators are in wide use. Will require high-temperature windings.	3	None required.
Software	Standard software approaches are available (e.g., ADA).	4	None required.

4.2.9 Power Conditioning System Technology Assessment

Table 4.2-9 summarizes the state of the art, needed research, and fallback positions for the components of the power conditioning system.

Table 4.2-9. Power Conditioning System Technology Assessment

Component or Assembly	State-of-the Art Assessment	Technology Readiness Level	Needed Research
Rectifier	Diode characteristics known, thermal calculation techniques standard in industry.	4	None required.
Cable	Change in design to flat aluminum plate (cable) allows adequate radiation heat loss to provide operation at moderate temperatures.	3	None required.

4.3 Development Schedule

4.3.1 System Development

Overall development schedules for the 10MWe and 200MWe systems are shown in Figures 4.3-1 through 4.3-4. The first two schedules are for a "crash" program (like the Apollo program), and the last two schedules are for a more typical program in which the rate of progress is a compromise between speed and availability of funding. In the "crash" schedule, program phases overlap.

The logic of all schedules is basically the same. The program starts with a system definition phase in which a preconceptual design is prepared primarily to assure that all research and development issues have been identified and characterized. A major output of this phase is a detailed plan for resolution of all feasibility issues.

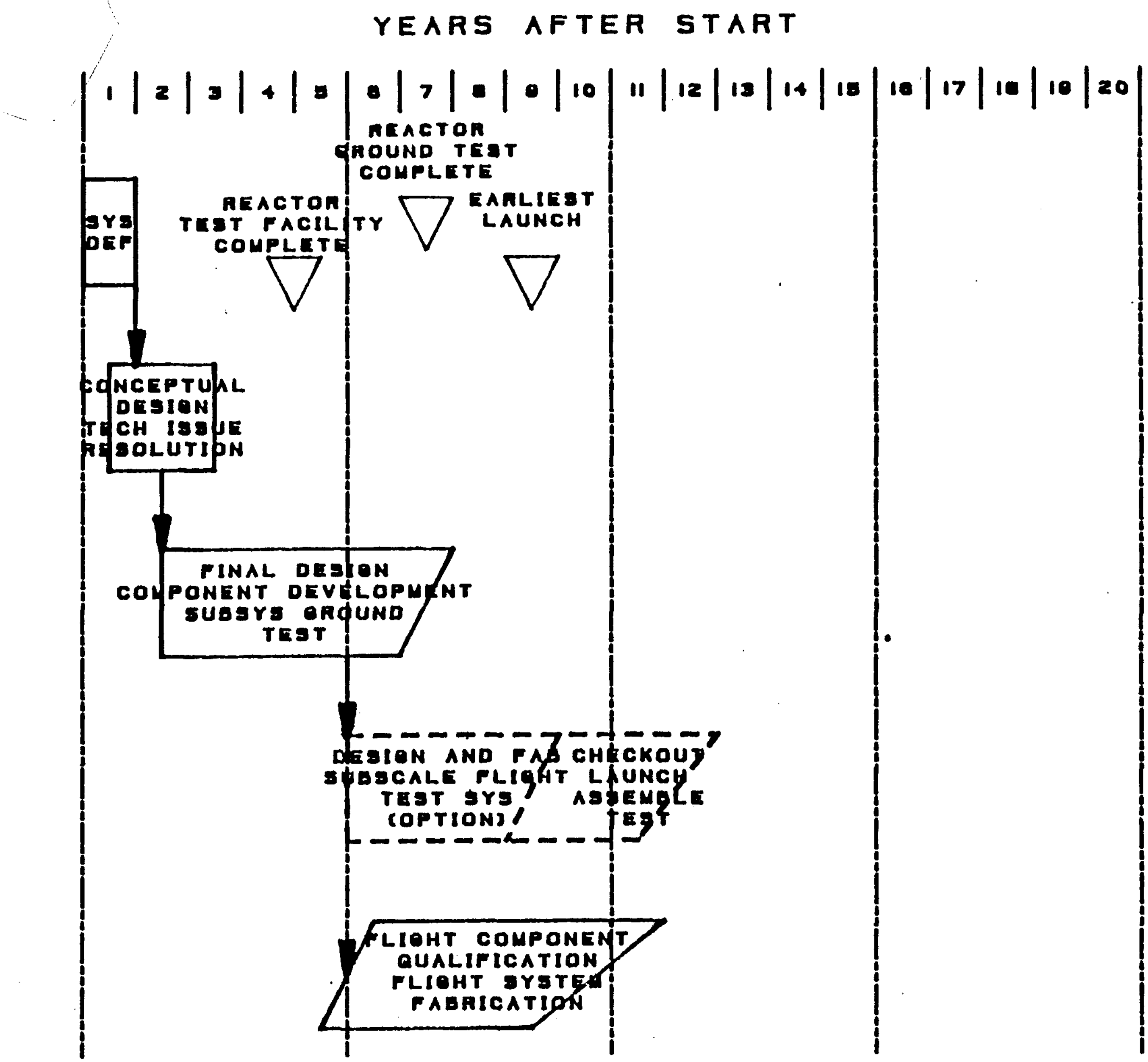
In the next phase of the program, the conceptual design of the system is prepared and more importantly, sufficient research is performed to resolve the technical feasibility issues. This phase is essentially the same for both the 10MWe and the 200MWe systems.

Full-scale development constitutes the next phase of the program. In this phase, each major system component is subjected to testing on the ground, in an environment approximating the ultimate operating environment, to verify performance. Design changes are made as necessary to achieve the desired component characteristics. Subsystem testing includes a reactor and primary loop ground test, and a separate (non-radioactive) test of a single power conversion loop.

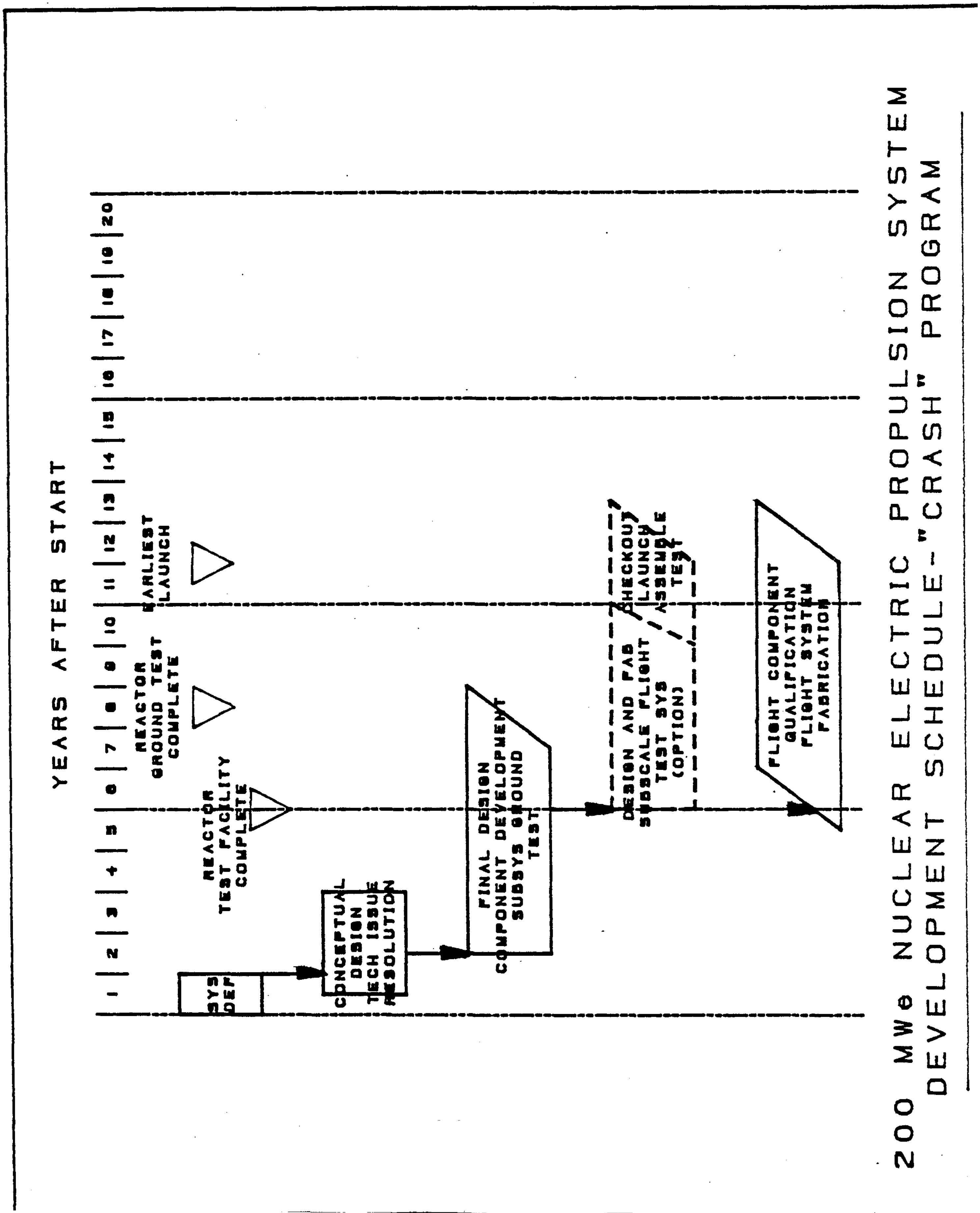
As an option, a subscale flight test system can be designed, fabricated, launched, and tested in space. Design of this flight test system can start several years into the full scale development phase, and it could be launched several years before the "full-up" system. Size of the subscale components would be determined based on scalability considerations, and the amount of redundancy (i.e., number of power conversion loops) could be minimized to keep costs down.

Successful completion of the full-scale development program leads to the next phase, in which all system components are flight qualified, and the flight system is fabricated.

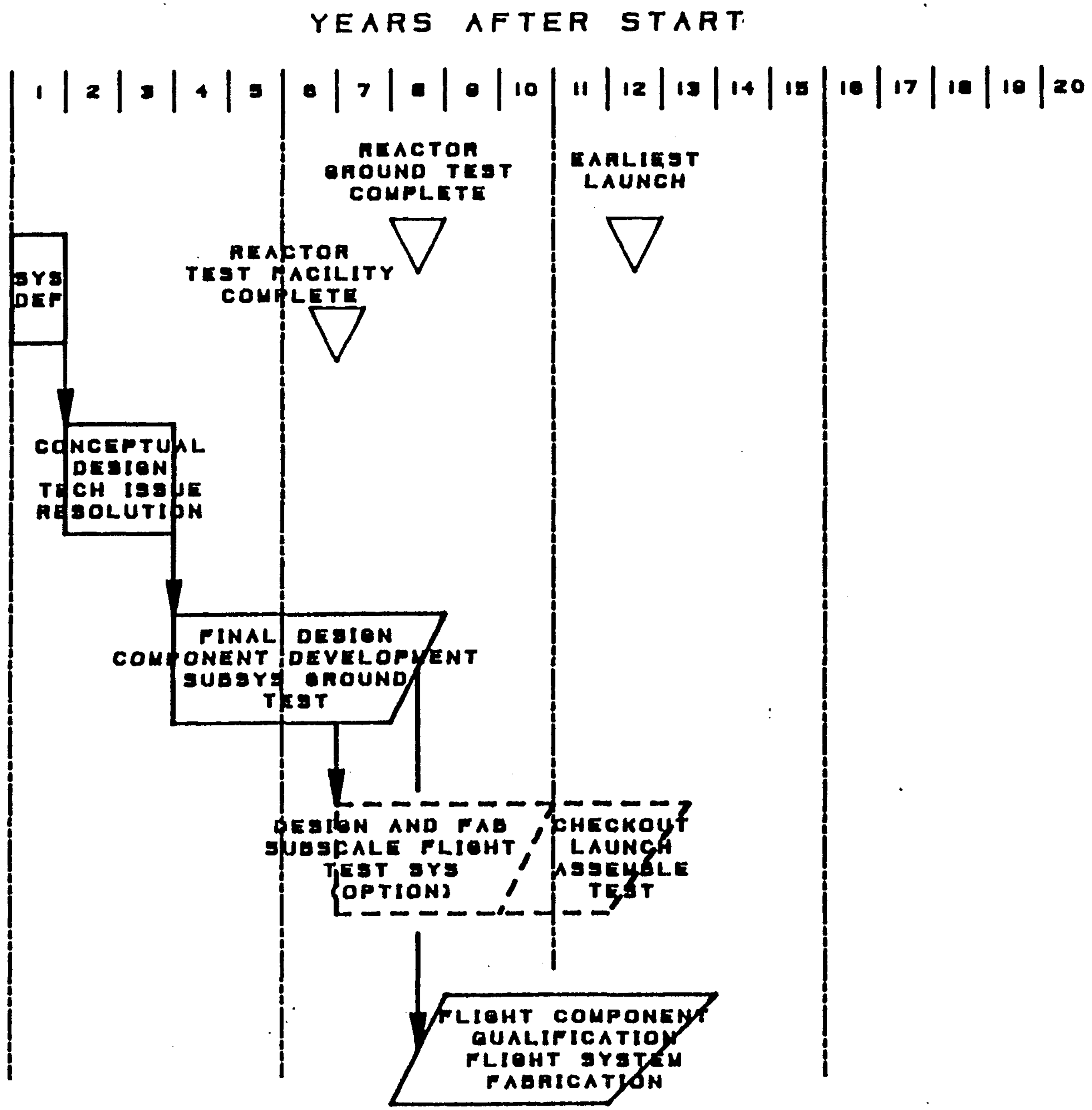
In the final phase, the flight system is launched, assembled in space, and tested to assure that it meets all performance requirements.



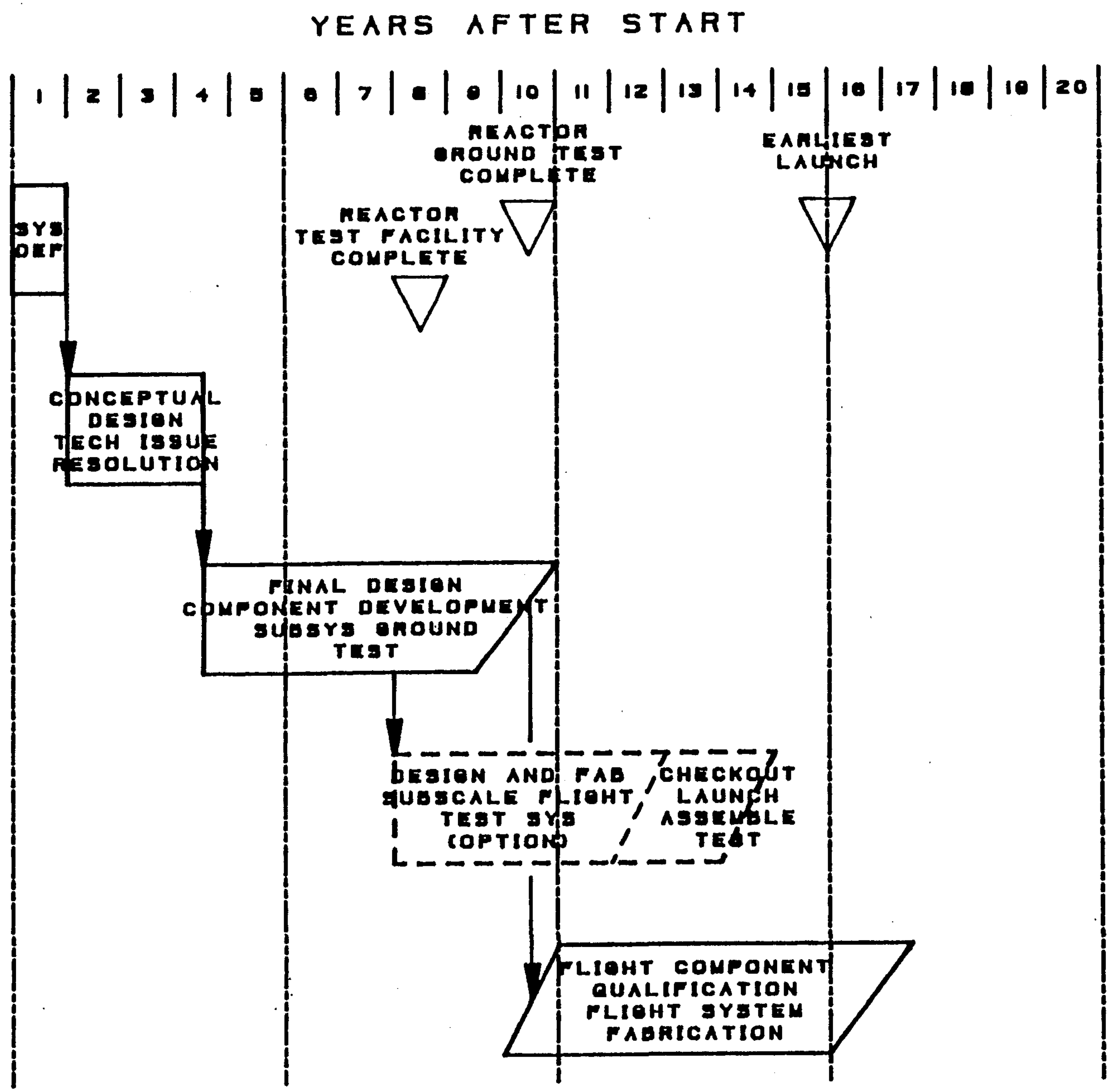
10 MWe NUCLEAR ELECTRIC PROPULSION SYSTEM DEVELOPMENT SCHEDULE-"CRASH" PROGRAM



200 MWe NUCLEAR ELECTRIC PROPULSION SYSTEM
DEVELOPMENT SCHEDULE - "CRASH" PROGRAM
YEARS AFTER START
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
SYS DEF
CONCEPTUAL DESIGN TECH ISSUE RESOLUTION
REACTOR TEST FACILITY COMPLETE
REACTOR GROUND TEST COMPLETE
EARLIEST LAUNCH
FINAL DESIGN COMPONENT DEVELOPMENT SUBSYS GROUND TEST
DESIGN AND FAB SUBSCALE FLIGHT TEST SYS (OPTION)
CHECKOUT LAUNCH ASSEMBLE TEST
FLIGHT COMPONENT QUALIFICATION FLIGHT SYSTEM FABRICATION



10 MWe NUCLEAR ELECTRIC PROPULSION SYSTEM DEVELOPMENT SCHEDULE-"NORMAL" PROGRAM



200 MWe NUCLEAR ELECTRIC PROPULSION SYSTEM DEVELOPMENT SCHEDULE-"NORMAL" PROGRAM

4.3.2 Test Facility Design and Construction

The major test facilities required for the development program are a reactor ground test facility and a nonnuclear subsystem test facility. For the 10 MWe system, these facilities can be designed and readied for operation at an estimated 4 years after program start at the very earliest. For the 200 MWe system, 5 years is a more likely estimate. These elapsed times support the "crash" program schedules for the two systems. For the "normal" program schedules, additional time would be utilized, both to allow time at the front end to establish firm requirements and during construction to minimize overtime. For this scenario, the major facilities for the 10 MWe system would be available in an estimated 6 years after program start and for the 200 MWe system, 7 years after program start.

4.4 Cost Estimate

Rough Order of Magnitude (ROM) costs have been estimated for the 10 MWe and 200 MWe system programs and are shown in Tables 4.4-1 through 4.4-4.

The cost estimates for the development costs include all necessary development tests, such as lithium thaw, power conversion system performance tests, radiator heat pipe development tests, reactor in-pile testing, etc. Also included are test facilities and test article costs. Finally, the development phase culminates with a ground demonstration test. Cost for the ground demonstration test facilities, test unit, and for the ground demonstration test are included. Total development costs come to 1.2 billion for the 10 MWe system, and 2.8 billion for the 200 MWe system.

Costs for the flight system design and qualification phase were developed on the basis of equipment similarity to other recent program cost estimates. These costs include costs for flight system design, component fabrication and qualification, systems mockup fabrication and qualification, and flight system fabrication and qualification. Qualification costs contain costs for test facilities, test article fabrication and acceptance, and qualification testing. Fabrication costs comprise costs for facilities, flight system components, and flight system assembly and acceptance. Systems mockup qualifications comprise thermal hydraulic qualification tests, structural qualification, and electromagnetic compatibility qualification. Total qualification costs come to $1.1 billion for the 10 MWe system, and $3.3 billion for the 200 MWe system.

The total ROM costs shown are for a "normal" program in which there is no significant overlap of program phases and for which the annual funding is sufficient to avoid delays or temporary cutbacks in effort. For a "crash" program, there would be a cost savings associated with "level-of-effort" activities such as program management, cost control and reporting, data management, etc. These costs typically run about 15% of the total program and tend to continue for the duration of the program. Shortening the duration decreases the costs. Countering these savings is the very real potential for cost increases due to overlap of program phases, coupled with requirement modifications or design changes initiated by the user. These changes, which occur frequently in complex programs, have a higher cost impact the faster the design and fabrication activities are moving.

For these reasons, only one set of costs has been estimated, and at the present state of system design and program planning, may be applied to either the "crash" schedule or the "normal" schedule.

TABLE 4.4-1

Development Costs – 10 MWe

• Program management		35M
• Preliminary design		127M
• Quality Assurance		5M
• Component development & Testing		509M
• Reactor	121M	
• Shield	46M	
• Power Conversion System	132M	
• Heat Rejection system	83M	
• Auxiliaries	21M	
• Plant control & power conditioning	106M	
• Ground demonstration		542M
• Facility	185M	
• Test article	325M	
• Testing	32M	
Total		1,218M

TABLE 4.4-2

Qualification Costs – 10MWe

• Management		33M
• Fabrication		448M
• Components	53M	
• System	395M	
• Testing		97M
• Components	54M	
• Systems	43M	
• Facilities		482M
• Safety		65M
Total		1,125M

TABLE 4.4-3

Development Costs – 200 MWe

• Program management		80M
• Preliminary design		191M
• Quality Assurance		7M
• Component development & Testing		564M
• Reactor	141M	
• Power Conversion System	168M	
• Heat Rejection system	96M	
• Auxiliaries	25M	
• Plant control & power conditioning	134M	
• Ground demonstration		1,955M
• Facility	455M	
• Test article	1,455M	
• Testing	45M	
Total		2,797M

TABLE 4.4-4

Qualification Costs – 200MWe

• Management		88M
• Fabrication		2090M
• Components	320M	
• System	1770M	
• Testing		130M
• Components	72M	
• Systems	58M	
• Facilities		651M
• Safety		80M
Total		3,039M

4.5 Advanced Technology Impact

As discussed in section 3.1.3, incorporation of certain advanced technologies in the design would be expected to improve system performance (i.e., decrease weight while retaining required electrical output). Counterbalancing these performance improvements is the additional time and expense required to develop the technology to the point where it can be utilized in the system with confidence.

The system mass savings and associated development time penalties for 1) advanced radiators, 2) carbon-carbon composites and piping, and 3) ceramic turbine materials have been roughly estimated and are tabulated in Table 4.5-1. If all three advanced technologies were incorporated, the total system mass savings would be additive, or about 6,480 kg for the 10 MWe system and 78,800 kg for the 200 MWe system. The schedule impact would be 5-7 years, since the additional radiator development time would envelop that for the turbine and the carbon-carbon components and piping.

TABLE 4.5-1
ADVANCED TECHNOLOGY IMPACT

ADVANCED TECHNOLOGY ITEM	SYSTEM MASS SAVINGS 10 MWE	SYSTEM MASS SAVINGS 200 MWE	DEVELOPMENT TIME PENALTY
ADVANCED RADIATORS (MOVING BELT)	2,000 KG	40,000 KG	5-7 YEARS
C-C COMPONENTS AND PIPING	3,000 KG	20,000 KG	3-5 YEARS
TURBINE BLADE MATERIAL	1,480 KG	18,800 KG	3-5 YEARS

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13. ABSTRACT ***(Maximum 200 words)***

The liquid metal cooled UN–W/25Re cermet fueled reactor selected as most appropriate for MMW potassium cycle applications in the DOE MMW program was employed in this study. The metallic matrix provides excellent thermal conductivity and constrains fuel swelling. A peak burnup of 25 percent should be achievable since the small UN fuel particles are only about 85 percent dense. The reference 200 MWe reactor with a 10 year lifetime weighs about 59 000 kg. It has been suggested that an alternate reactor concept, which uses liquid metal cooled recirculating tungsten or molybdenum clad UC_2 fuel pellets could result in a reactor mass of about 10 000 Kg. However, a definitive conceptual design for such a reactor concept has not been developed and the compatibility and burnup capability of the clad carbide fuel is too uncertain to consider for a reference reactor mass. Although a reactor mass of 10 000 Kg appears too optimistic for a 200 MWe 10-year recirculating pellet fueled reactor, perhaps a mass savings of 15 000 to 20 000 Kg over the reference approach might be possible if such a design ever proved feasible. The potential system mass savings for the 200 MWe two-year of 10 MWe systems could not be near as significant.

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